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RADIO EMISSIONS AND THE NATURE OF THE MOON

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RADIO EMISSIONS AND THE NATURE OF THE MOON /589

V. D. Krotikov and V. S. Troitskiy

1. General Information on Physical Conditions on the Moon and Its Radio Emissions

As late as the 1930's the only source of information regarding physical conditions on the moon was the solar radiation reflected from its surface. Naturally, this radiation could only convey information concerning the state of matter on the very surface, and even then more about its microrelief (coarseness, grain size, etc.) than the nature of the substance and its properties. By now the properties of the lunar surface have been well investigated through reflection of light rays (reflectivity, polarization properties, etc.). The French school of astronomers has made great contributions in this field: Lyot, Dollfus and others.

An extremely large contribution has been made by the Khar'kov school of astronomers, headed by N. P. Barabashov (A. T. Chekirda, V. I. Yezerskiy, V. A. Fedorets and others), and the Leningrad school, under the supervision of V. V. Sharonov (N. N. Sytinskaya, N. S. Orlova, L. N. Radlova and others). Significant works have been carried out by V. G. Fesenkov, A. V. Markov, A. V. Khabakov and B. Yu. Levin. It is also appropriate to mention the polarization investigations of V. P. Dzhapiashvili. As a result of these broad investigations many different properties and regularities of reflection and scattering of light by the lunar surface have been established (see for example Reference 56). However, the conclusions which are of interest to us may be reduced to to those which state that the lunar surface is very coarse or consists of finely granulated substances.

The reflectivity and polarization properties of the lunar matter do not resemble any of the terrestrial rocks in the natural or in the pulverized state.

Toward the end of the 1920's and the beginning of the 1930's the moon was studied by its own thermal electromagnetic radiation in the infrared region of 10-15 μ wavelengths. Measurements of Pettit and Nicholson in 1927 and 1930 (Ref. 5) during lunation enabled the determination of surface temperature, and measurements during lunar eclipses (Refs. 5, 58) enabled Wesselink (1948) (Ref. 1) and then Jaeger (1953) (Ref. 2) to find thermal conductivity of the lunar substance, which was determined to be so small that it could only correspond to fine dust, existing in a vacuum. Measurements of the thermal conductivity of powders in a vacuum, conducted by Smoluchowskiy (1911) (Ref. 65), substantiated this assumption. /590

Thus, the uniform dust layer hypothesis originated. More detailed analyses have shown that this dust on the surface of cliffs forms a layer which is only several millimeters in thickness (Ref. 59).

In 1949, Piddington and Minnett were the first to conduct investigations of thermal radiation from the moon on a 1.25 cm waveband. They came to a conclusion regarding the two-layer dust structure of the upper layer of the lunar surface and also evaluated the magnitude of the effective electrical conductivity of the lunar matter on the 1.25 cm band. The significance of this work lies in the discovery that radio emission from the moon is determined by a thick layer of substance and that this emission carries the information regarding the physical properties of the whole layer, rather than just of the surface, as is the case with reflected light rays and infrared radiation. However, the significance of this became clear only at the present time, when radio emission gave significant results which before had appeared unachievable.

Some time after the first measurements, an intensive investigation of lunar radio emission on different wavelengths and the development of methods for determining physical conditions on the moon (temperature, thermal and electrical properties of lunar matter, its structure and nature) was begun.

Investigation of the moon by radio emission was carried on in a number of countries by different authors. A large volume of work has been completed on this subject. However, the most systematic investigations of the moon were performed in the Soviet Union by a group of radio astronomers at the NIRFI [Nauchno-Issledovatel'skiy Radiofizicheskiy Institut; Scientific Research Institute of Radiophysics] and at Gor'kiy State University [Gor'kovskiy Gosudarstvenyy Universitet], starting from 1950 and carried up to the present time (Refs. 3, 4, 8, 11-14, 16, 24-26, 28-30, 34-38, 40, 50, 52, 53, 63, 67-70, 72, 76). Other studies were made by a group of radio astronomers at the FIAN [Fizicheskiy Institut AN SSSR; Physics Institute of the Academy of Sciences of the USSR] starting in 1955, under the direction of A. Ye. Salomonovich (Refs. 9, 10, 20-23, 29, 32, 76) and at Pulkovo Observatory of the Academy of Sciences of the USSR [GAO; Glavnaya Astronomicheskaya Observatoriya; The Main Astronomical Observatory] under the direction of S. E. Khaykin and N. L. Kaydanovskiy (Refs. 10, 71, 81).

The investigations of lunar radio emission and of terrestrial rocks recently conducted at NIRFI gave many new results and enabled the creation of a sufficiently complete, internally consistent picture of the physical properties of the upper layer of the moon. The progress in this direction is wholly dependent on the development of a new precise method for measuring the lunar radio emission with an accuracy not less than ± 1-2 percent. Since later we shall not be concerned with measurement methods of lunar radio emission it is worthwhile to pause on this subject now. Let us establish definitions and concepts which are connected with lunar radio emission.

As is known, lunar radio emissions are thermal. The moon is not an absolute black body to radio waves, and therefore the intensity of radiation from any part of its elementary area is characterized by the effective (brightness) temperature, which is understood to be the temperature of an absolute black body, which gives the observed intensity of radiation. More often the effective temperature obtained by radio wave meas- /591
urements is called radio temperature. The brightness radio temperature is not the same for the whole lunar disk and is distributed along the disk in correspondence with the distribution of true temperature and emissivity of the surface. All of the utilized methods for measuring the intensity of lunar radio emission give some mean value of radio temperature along the disk (the weighted mean along the diagram), equal to (Refs. 8, 37)

$$\bar{T}_1 \longrightarrow \bar{T}_{\text{Л}} = \frac{\int\limits_{\Omega_{\text{Л}}} F(\Omega)\, T_{\text{Л}}(\Omega)\, d\Omega}{\int\limits_{\Omega_{\text{Л}}} F(\Omega)\, d\Omega},$$

where T_1 is the distribution function of the brightness radio temperature along the lunar disk, Ω_1 is the solid angle of the moon and F is the equation of the antennae diagram in terms of power.

When the antenna has the width of a whole disk much smaller than the angular dimensions of the moon, then the measurements are of practically the mean radio temperature along the disk:

$$\bar{T}_{\text{Л}} = \frac{1}{\Omega_{\text{Л}}} \int\limits_{\Omega_{\text{Л}}} T_{\text{Л}}(\Omega)\, d\Omega.$$

To determine the magnitude of $\bar{T}_1$ it is necessary to measure the quantity

$$\int\limits_{\Omega_{\text{Л}}} F T_{\text{Л}}\, d\Omega,$$

which is proportional to the power of the signal at the output of the antenna. The proportionality coefficient is a function of the parameters of the antenna (directionality, losses, diagram). By measuring the power of the signal at the output of the antenna by means of radiometers and knowing the parameters of the antenna, it is easy to determine the desired magnitude of radio temperature. However, this method, which is normally used, contains significant errors due to the difficulty of determining antenna parameters and to a lesser extent due to the inaccuracy of determining the output signal power. The accuracy of such measurements of $\overline{T}_1$ generally does not exceed 10-20 percent, which in essence makes the measurements relative. This places great limitations on the possibility of using radio data for the determination of temperature and physical parameters of the surface layer. However, from the relative data it was possible to establish that the upper layer of the moon has approximately uniform properties which do not vary with depth. It was also possible to make other conclusions from these relative measurements, which shall be treated later.

New results were obtained using the precision measurement method, developed at NIRFI (Ref. 24). This method of measurement of lunar radio temperature is based on comparison of its radio emission with the accurately known emission of the absolutely black disk, placed in the Fraunhofer zone of the antenna at sufficient angular elevation above the horizon. The power of the signal from the disk is proportional to

$$T_d \longrightarrow T_{\text{д}} \int_{\Omega_{\text{д}}} F \, d\Omega$$

where T_d is the temperature of the disk. Utilizing this quantity it is easy to calibrate the whole system without the measurement of the antenna output power and without the use of inaccurately known antenna parameters. This method is known as the "artificial moon" method, since generally the angular dimensions of the disk as viewed by the radio telescope antenna are close to the angular dimensions of the moon. It /592
appears that the most significant error of this method is associated with the effect of the earth's radio emission, which is diffracted on the disk and is perceived by radio telescope, thus increasing the standard signal by some indeterminate quantity. To eliminate the effect of diffraction a second standard is used in the form of an opening in a plane which covers the main leaf of the antenna diagram and is located in the same point as the disk. The opening corresponds exactly to the size of the disk. In this case the standard signal, produced by the emission from the disk placed in an opening, appears to be decreased by the magnitude of diffracted radio emission in the opening. Since diffraction patterns of the disk and the opening are identical (with auxiliary screens) the magnitude of diffraction will be equal.

Consequently, the mean value of signals from the free disk and from the disk in an opening will be rigorously equal to the known emission of the disk.

Later, due to the use of the second standard, conditions were found for mounting the disk so that the magnitude of terrestrial radio emission was lowered to a negligibly small magnitude and then only one standard disk was used. The dimensions of disks in the first measurements with a 3.2 cm band and with 1.5 m diameter antenna were 60 and 120 cm, and later 4-5 m. Figure 1 shows a photograph of the apparatus for observations with a 5 m diameter disk, placed on a mountain near the ruins of the Genoese fortification in Sudak. Figure 2 shows a similar apparatus in Kara-Daga in the Crimea. Figure 3 shows a 4-meter artificial moon.

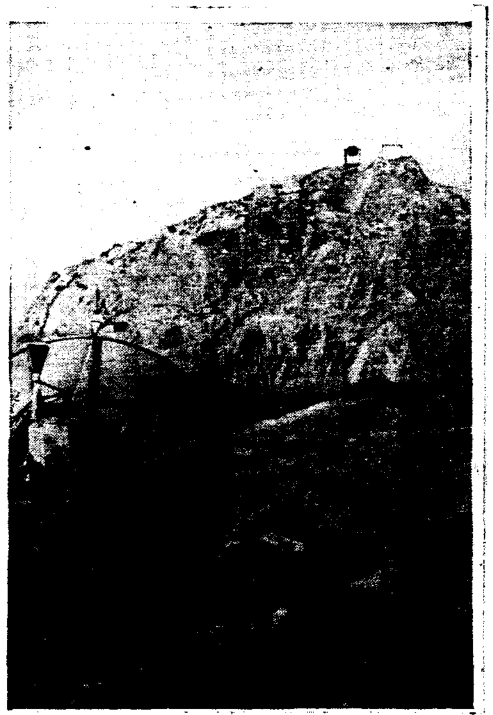

Figure 1. Observation of radio emission from a standard disk, 5 m in diameter, placed on a mountain near the town of Sudak

The results of the new method showed that it is possible to determine the temperature of the moon with 2-3 percent accuracy in a broad range of wavelengths. However, this method is possible, from the technical standpoint, only for measurement of the integral radiation, i.e., the mean radio temperature over the lunar disk.

In the course of not more than a decade of lunar investigations by radio emission, significant results were obtained which uncover the nature and physical conditions not only of the upper layer, but also of the deep interior of the moon, shedding light on its past history. The obtained results may be reduced to the following:

Figure 2. Observation of radio emission from a standard disk, 4 m in diameter, placed on Kara-Daga in the Crimea

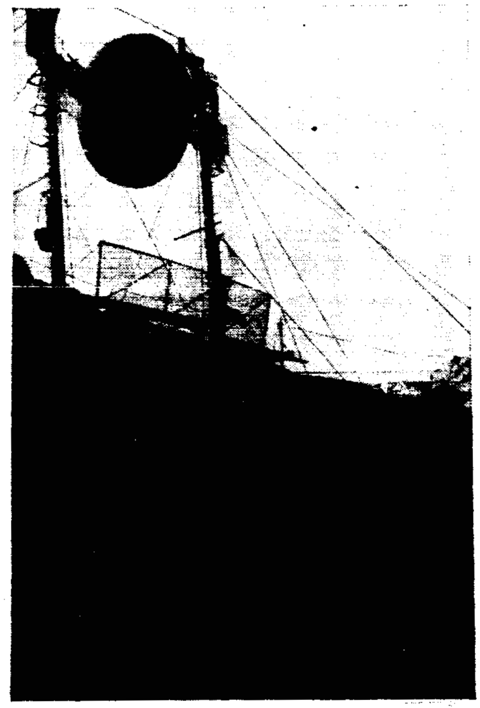

Figure 3. "Artificial moon" four meters in diameter

1. The mean temperature conditions of the lunar surface have been investigated. The temperature distribution along the lunar disk and its dependence on time has been established. The mean temperature on the surface for the equator of the moon equals $T_0(0) = 230^\circ K$, and the amplitude of the first harmonic $T_1(0) = 155^\circ K$. At a depth of 1-1/2 m temperature fluctuations are practically nonexistent.

2. The temperature increase was established into the interior of /593
the moon at a rate of 1.6 deg/m to a depth of 20 m. The thermal flux density from the interior of the moon was established. It is equal to that of the earth - $1.3 \cdot 10^{-6}$ cal/cm$^2 \cdot$sec.

3. An approximate uniformity of substance from the upper layer of the lunar surface down to a depth of 20 m was established. The measured density of substance in this layer is close to 0.5 g$\cdot$cm^{-3}. The whole 20 m layer is in an extremely porous state of aggregation, in the form

of solid foam, having a thermal conductivity which is 40-60 times less than the conductivity of dense terrestrial rocks.

4. The dielectric loss angle of lunar matter on super-high frequencies (or effective electrical conductivity) was found was found to be $5 \cdot 10^{-3}$ per $g \cdot cm^{-3}$, which corresponds to losses in good industrial dielectrics. The obtained data on chemical and mineralogical properties of lunar substance indicate that it consists of quartz to the extent of 60-65 percent, and possibly close to the granite group, but different in structure.

5. The yearly lunar thermal flux has been determined as equal to $1.6 \cdot 10^{19}$ cal/year. Assuming radiogenic origin of this heat the mean concentration of radioactive elements for the moon has been evaluated, and is found to be greater than the mean concentration for the earth by a factor of 5-6. The temperature of the lunar interior has been evaluated. This is an incomplete list of the obtained results.

The purpose of this review is not only to give more complete information about the physical conditions on the moon, obtained as a result of lunar emission, but also to uncover means and methods of analysis for the determination of these conditions.

2. Lunar Surface Temperature /594

It is well known that the temperature of the surface of the moon is determined by solar radiation heating. Due to the absence of atmosphere on the moon it is possible to conduct accurate calculations of its surface temperature at a given magnitude and change of the radiant flux from the sun. Wesselink (Ref. 1) was the first to consider the thermal conditions of the lunar surface during lunation for the center of the visible disk.

It is known that the nature of temperature changes of any body under a given change of flux is completely determined by some thermal parameter $\gamma = (k\rho c)^{-1/2}$, where k is the thermal conductivity, ρ is the density and c is the heat capacity (at constant pressure) of the material of which this body is composed. In Reference 1 theoretical calculations were made of thermal conditions assuming uniform thermal properties of the surface layers of the lunar crust (k and ρ are independent of depth) for a single value of the parameter $\gamma = 920$. More detailed calculations of thermal conditions for the center of the disk were conducted by Jaeger (Ref. 2). In his calculations a homogeneous model of the structure of the upper layer was assumed with different assumptions regarding its thermal properties, and also a two layer, sharply inhomogeneous model, according to which the lunar surface is pictured as consisting of continuous rock with low value of thermal parameter $\gamma = (k\varrho c)^{-1/2} \approx 100$, covered with a thin layer of dust for which $\gamma = 1000$. To determine the changes of temperature of the surface in the center of the visible lunar disk in the course of the lunar cycle Jaeger solved a thermal conductivity equation for the case of periodic thermal flux from the sun and emission according to the Stefan-Boltzman law, see formulae (1) and (2). Calculations were conducted by the numerical integration method. However, the author utilized a value for the solar constant which is too low ($A_0 = 1.55$ cal/cm^{2}min) and he assumed that in the initial moment the upper layer of the moon is heated uniformly.

It is known that the value of the solar constant is $A_0 = 2$ cal/cm^{2}min.

As a result of the investigation of lunar radio emission it was shown that the surface layer of lunar matter has a quasi-homogeneous structure into the interior. Thus a sharply inhomogeneous model must be disregarded as it does not correspond to the experimental data (Ref. 3). In connection with this (Ref. 4) the temperature conditions of the lunar surface have been more rigorously investigated with the utilization of a new value for the solar constant and of the indicated new data on the structure of the upper layer. Utilizing the high speed electronic computer BESM-2 for any point of the lunar surface with selenographic substance coordinates φ, ϕ and for parameter γ, equal to 20, 125, 250, 400, 500, 700, 1000 and 1200 a steady state solution of the following equation was found

. (1)

with boundary conditions

$$\left.\begin{aligned} k\frac{\partial T}{\partial y} &= E_1\sigma T^4 - A_0\cos\psi E_2\cos(\Phi-\varphi) \quad \text{for} \quad |t| < \tfrac{1}{4}\tau, \\ k\frac{\partial T}{\partial y} &= E_1\sigma T^4 \quad \text{for} \quad \tfrac{1}{4}\tau < t < \tfrac{3}{4}\tau. \end{aligned}\right\} \qquad (2)$$

Here $a = k/\varrho c$, thermal conductivity coefficient, $A = 2$ cal/cm^{2}min, solar constant, E_1 is emissivity in the maximum region of natural thermal radiation of the lunar surface, E_2 is emissivity in the wavelength region of the incident light flux, τ is the lunation constant, $\Phi = \Omega t$, phase angle, Ω is the lunation frequency, and σ is the Stefan-Boltzman constant.

Since the problem was solved until steady state solution, then any starting conditions may be chosen. Figure 4 shows the dependence of surface temperatures on time in the center of the lunar disk, referred to as a lunation period. Broken lines correspond to Jaeger's calculations for γ = 20 and 1000. Comparison of the obtained curves with Jaeger's calculations (Ref. 2) shows that in the latter the values of surface tem- /595

perature for points illuminated by the sun are almost 20° lower (375°K)

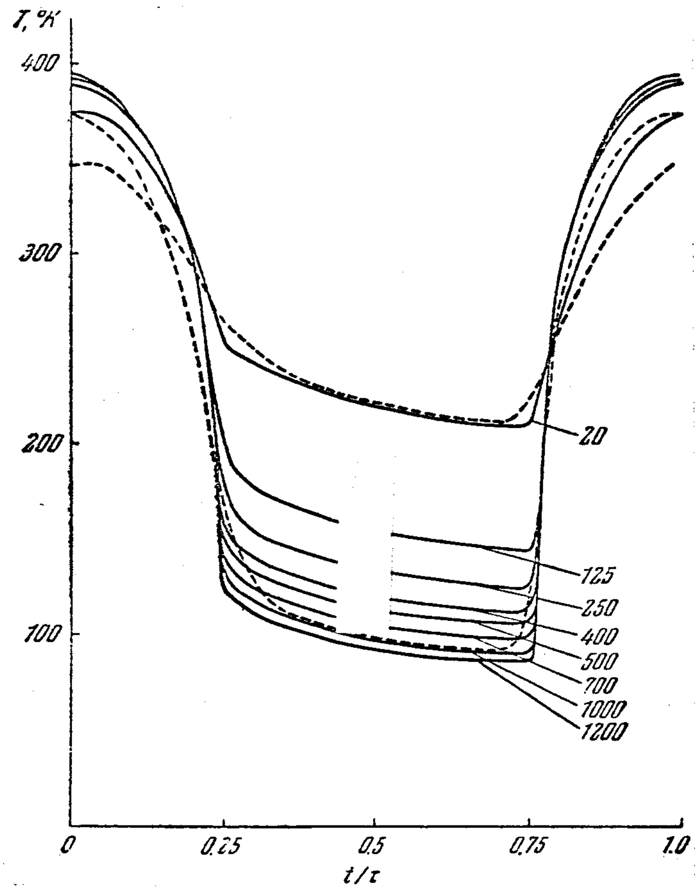

Figure 4. Variation of the surface temperature in the center of the lunar disk as a function of reduced lunation period for different values of parameter γ. Broken lines correspond to calculations of Jaeger (Ref. 2) for γ = 20 and γ = 1000

than the corresponding value obtained in (Ref. 4). In Reference 2 the temperature drop between day temperature T_m and night temperature T_H is

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smaller by approximately the same amount. Sharper transition in Reference 4 at points $t/\tau = 0.25$ and $t/\tau = 0.75$, corresponding to sunset and sunrise, is apparently caused by the fact that subdivision of lunation period into 20 parts aids the smoothing of curves at these points in Reference 2. Figure 5 shows the relationships of the temperature of the sunlit point T_m, constant component T_0, amplitude of the first harmonic T_1, and night temperature T_H for the center of the lunar disk as a function of parameter γ.

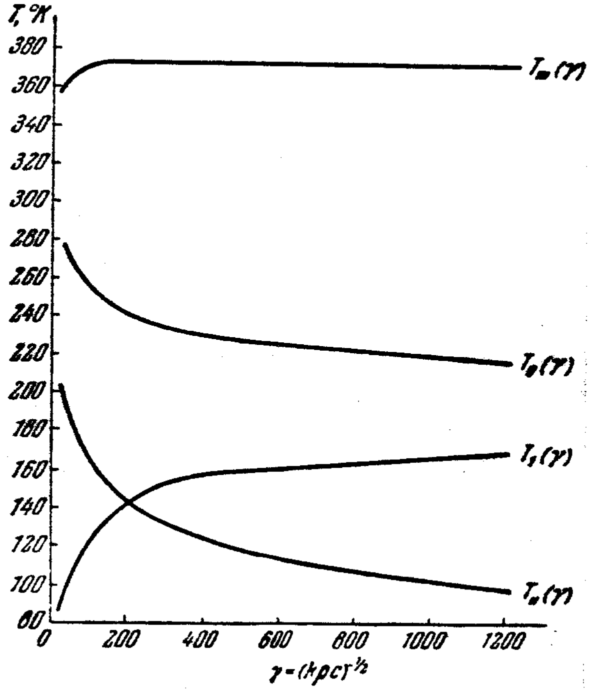

Figure 5. The temperature of sunlit point T_m, the constant component T_0, the amplitude of the first harmonic T_1 and night temperature T_H as a function of parameter $\gamma = (k\rho c)^{-1/2}$

The surface temperature at a sunlit point is completely determined by the incident light beam and is therefore practically independent of parameter γ, while the night temperature depends on it significantly. The larger the quantity γ the faster the lunar surface cools and the lower the night temperature. This leads to a decrease of the constant component and to an increase of the first harmonic amplitude. Solution /596

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of the thermal problem for values of emissivity, which changes within the $0.9 \leq E_1, E_2 \leq 1$ limits showed that the temperature of the surface changes by 2 percent.

The effect of the solar constant on the temperature of a sunlit point and on night temperature is represented in Figure 6. Changes of the solar constant within broad limits are significantly reflected on the temperature of the sunlit point and have practically no effect on the night temperature. The insignificant change of the solar constant due to the eccentricity of the orbit of the earth has practically no effect on the temperature of the lunar surface.

In calculations of lunar radio emission it is worthwhile to obtain an analytical expression for the intensity of radio emission. For this it is necessary to know the analytical expression for the temperature distribution along the depth. It is obtained by solving the thermal conductivity expression if the desired temperature is on the surface. The most convenient form of assigning surface temperature is a function which is represented in the form of a Fourier series. Therefore, calculation results of the surface temperature are represented in the form (Ref. 4)

$$T(\varphi, \psi, t) = T_0(\psi) + \sum_{n=1}^{4} (-1)^{\alpha_n} T_n(\psi) \cos(n\Phi - n\varphi - \psi_n). \qquad (3)$$

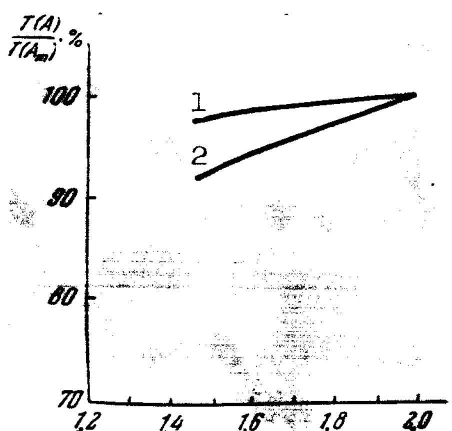

Figure 6. Change of relative temperature of sunlit point (curve 2) and of relative night temperature (curve 1) as a function of solar constant

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where φ is the longitude and φ is latitude of the point, φ_n is the phase shift for the n-harmonic of surface temperature change with respect to the phase of the incident flux. The sign of the first four harmonics is determined by the exponent

$$\alpha_n = \frac{(n-1)(n-2)}{2}.$$

As was shown in Reference 4 the first five values of $T_n(\psi)$ are well approximated by the expressions

$$\left.\begin{array}{ll} T_0(\psi) = T_0(0)\cos^{0.2}\psi, & T_3(\psi) = T_3(0)\cos^{0.44}\psi, \\ T_1(\psi) = T_1(0)\cos^{0.33}\psi, & T_4(\psi) = T_4(0)\cos^{0.3}\psi. \\ T_2(\psi) = T_2(0)\cos^{0.27}\psi, & \end{array}\right\} \tag{4}$$

Here $T_n(0)$ is the value of the corresponding magnitudes of temperature harmonics in the center of the lunar disk. /597

The obtained expressions (4) for distribution of various components along the disk are practically independent of parameter γ for changes within the $125 \leq \gamma \leq 1200$ limits. The numerical values of the constant component $T_0(0)$ and of the amplitudes of harmonics $T_n(0)$ as well as corresponding phase shifts φ_n are represented in Table I as a function of the magnitude of γ. The solution of the problem on a computer also gives the distribution of temperature along the depth y at any point (φ, ψ). The knowledge of the temperature distribution function along the lunar surface (3) enables one to solve the thermal conductivity equation (1) with boundary conditions assigned in the form of a harmonic series (3). As a result we shall obtain for any point (φ, ψ) on the lunar surface a temperature distribution along the depth in the form of

$$\begin{aligned} T(y, \varphi, \psi, t) = T_0(\psi) + \\ + \sum_{n=1}^{4} (-1)^{\alpha_n} T_n(\psi)\, e^{-y\sqrt{\frac{n\Omega}{2a}}} \times \\ \times \cos\left(n\Phi - n\varphi - \varphi_n - y\sqrt{\frac{n\Omega}{2a}}\right). \end{aligned} \tag{5}$$

It is apparent that the temperature at any depth is composed of a time independent temperature, known as a constant component, and a variable component, which is formed by a sum of harmonics with a period which is a multiple of the lunation period (τ = 29.53 days).

Table 1. Numerical Values of Elements of Fourier Expansion of Surface Temperature in the Center of the Lunar Disk as a Function of γ

γ	$T_0(0)$, °K	$T_1(0)$, °K	$\varphi 1$, deg	$T_2(0)$, °K	$-\varphi 2$, deg	$T_3(0)$, °K	$\varphi 3$, deg	$T_4(0)$, °K	$-\varphi 4$
125	247	132	5	34	6	19	11	13	7
250	237	146	4	35	7	23	6	14	9
400	230	156	3	36	7	26	6	15	9
500	227	159	3	36	7	28	5	15	9
700	223	165	3	36	7	30	4	15	9
1000	219	170	2	36	6	31	3	15	9
1200	217	173	2	36	6	32	3	15	8

Each of the harmonics is damped as it proceeds into the depth and at a

$$l_{Tn} = \sqrt{\frac{2a}{n\Omega}}$$

depth the amplitude of temperature oscillations decreases by a factor e as compared with surface values. In the future this depth will be called the penetration depth of the temperature wave and for the first harmonic it will be equal to

$$l_T = \sqrt{\frac{2a}{\Omega}} = \sqrt{\frac{2k}{\varrho c \Omega}}. \qquad (6)$$

At a depth which exceeds l_T by a factor of 3-4 the temperature oscilla- /598 tions are practically absent. The magnitude of l_T characterizes the thickness of the layer of rocks which is heated by the sun in the course of a lunar day.

The law which governs surface temperature change as a function of latitude ψ was used in References 7 and 8 during analytical solution of the problem of lunar radio emission. Here Piddington and Minnett assume that constant component of the surface temperature depends on latitude and obeys the law

$$T_0 = T_0(0) \cos^{1/4} \psi. \qquad (7)$$

In Reference 8 it was assumed that the temperature of any point on the surface of the moon is equal in the general form to

$$T(\varphi, \psi, t) = T_H + (T_m - T_H)\,\eta(\Phi - \varphi)\,\eta(\psi), \qquad (8)$$

where $\eta\ (\Phi - \phi)$ and $\eta\ (\psi)$ is the temperature distribution above the night temperature, T_m is the sunlit point and T_H is the night temperature.

On the basis of Jaeger's curves for temperature changes during lunation it was found (Ref. 14) that $\eta\ (\psi) = \cos^{1/2} \psi$, $\eta = (\Phi - \varphi) = \cos^{1/2} (\Phi - \varphi)$. Decomposition of the relationship (8) into Fourier series with time gives the following expression for the constant component

$$T_0 = T_H + a_0 (T_m - T_H) \cos^{1/2} \psi, \tag{9}$$

where $a_o = 0.387$ - the Fourier decomposition coefficient for changes of surface temperature. The distribution (9)-(8) accepted in Reference 8 and utilized to the present day in practice coincides with the accurate distribution (3)-(4). A significant difference will be observed only near the pole. Let us compare the obtained temperature distribution with the experimental values.

The first measurements of infrared temperature were conducted by Pettit and Nicholson (Ref. 5). They obtained the value of temperature on a sunlit point equal to $T_m = 391^oK$. Later Sinton and others (Ref. 6) found $T_m = 389^oK$. These numbers agree with the values of temperature of a sunlit point, which have been obtained in Reference 4. However, in foreign literature the temperature $T_m = 374^oK$ found by Pettit and Nicholson from theoretical calculation is still used. In Reference 5 it was shown that temperature distribution function is dependent on the angle of incidence of rays r and deviates from the law $\cos^{1/4} r$, which corresponds to the smooth surface. In reality one observes the following law

$$T(r) = T_m \cos^{1/6} r \tag{10}$$

Naturally the distribution calculated in Reference 4 will be somewhat lower in temperature near the limb of the moon than is given by expression (10). This discrepancy occurs at $r > 45\text{-}50^o$, i.e., within the limits of 3-4 angular minutes near the limb of the moon. The deviation of temperature distribution from the theoretical law $\cos^{1/4} r$, is explained by the authors as due to the great coarseness of the surface.

Measurements of the distribution of the lunar radio brightness on the 0.8 and 2 cm waves with the 22 m diameter telescope of FIAN (Ref. 9) enable use of the method which was proposed by N. L. Kaydanovskiy and A. Ye. Salomonovich (Ref. 10) to determine function $\eta(\psi)$ which is found to be approximately $\eta(\psi) = \cos^{1/2}\psi$.

3. The Theory of Lunar Radio Emission /599

Lunar radio emission is thermal in nature and its main characteristics are determined by conditions of heating and cooling of the surface layer during lunation.

Originally, the theory of radio emission from the moon was given by Piddington and Minnett in 1949 (Ref. 7) in connection with the observations of the 1.25 cm band of radio emission from the moon as a function of its phases. During calculations it was assumed that lunar matter is a dielectric, permitting propagation of waves with a certain damping. Radio emsiion from such material proceeds basically from the layer whose optical thickness equals unity. This layer apparently has its lower boundary at a depth $l_э$, from which radio emission is radiated weakened by e = 2.73 times. All characteristics of the phase relationship of lunar radio emission, as was shown in Reference 7, are determined by the relationship between the thickness of the radio emitting layer $l_э$ and the thickness of the rock layer which is heated by the sun l_T. Thus, the nature of the dependence of lunar radio emission on its phase is determined by the electric (angle of losses) as well as the thermal (thermal conductivity, density, heat capacity) properties of its substance.

The detailed consideration of the theory of lunar radio emission was presented in Reference 8. Here is was assumed that the surface of the moon is sufficiently smooth for radio waves and that Fresnel's formulae for the reflection coefficient are valid. In addition, it was assumed that the substance in the upper layer is homogeneous in depth with respect to its thermal and electric properties, i.e., it has identical density to a certain depth. According to Reference 8 the effective radio emission temperature of an element of lunar surface with coordinates φ, ψ is equal to

$$T_e = [1 - R(\varphi, \psi)] \int_0^\infty T(y, \varphi, \psi, t)\, \varkappa \sec r' \cdot e^{-y\varkappa \sec r'} dy, \tag{11}$$

where T (y, φ, ψ, t) is the true temperature of the lunar substance at a depth y at the time t, given by the expression (5), R (φ, ψ) is the reflection coefficient which corresponds to vertical or horizontal polarization, $\varkappa$ is the absorption coefficient of electromagnetic waves which is independent of y for the considered case of a uniform structure of the upper layer of the moon, r' is the angle between the direction of

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radiation which comes from the interior and the normal to the surface element at the exit of this radiation. After the substitution of the temperature distribution along the depth in the form of expression (5) into equation (11), which is different from Reference 8, one obtains the following expression for the effective temperature of the element of lunar surface:

$$T_e(\varphi, \psi, t) = [1 - R(\varphi, \psi)] \Big\{ T_0(\psi) + \sum_{n=1}^{4} (-1)^{\alpha_n} T_n(\psi) \int_0^{\infty} \varkappa \sec r' \cdot e^{-y\left(\sqrt{\frac{n\Omega}{2a}} + \varkappa \sec r'\right)} \times \cos\left(n\Phi - n\varphi - \varphi_n - y\sqrt{\frac{n\Omega}{2a}}\right) dy \Big\}. \qquad (12)$$

From here according to Reference 8

$$T_e(\varphi, \psi, t) = [1 - R(\varphi, \psi)] \Big\{ T_0(\psi) + \sum_{n=1}^{4} (-1)^{\alpha_n} \frac{T_n(\psi)}{\sqrt{1 + 2\delta_n \cos r' + 2\delta_n^2 \cos^2 r'}} \cos\left(n\Phi - n\varphi - \varphi_n - \xi_n(\varphi, \psi)\right) \Big\}, \qquad (13)$$

/600

where

$$\delta_n = \frac{\sqrt{\frac{n\Omega}{2a}}}{\varkappa}.$$

This relationship represents the ratio of the penetration depth of the electromagnetic wave $l_э = 1/\varkappa$ to the penetration depth of the n-harmonic of the thermal wave

$$l_{nт} = \sqrt{\frac{2a}{n\Omega}}, \quad \cos r' = \frac{1}{\sqrt{\varepsilon}} \sqrt{\varepsilon - \sin^2 r},$$

where r is the angle between the normal to the surface and the direction to the receiving point,

$$\xi_n(\varphi, \psi) = \operatorname{arctg} \frac{\delta_n \cos r'}{1 + \delta_n \cos r'}$$

is the phase shift for the n-harmonic of the effective temperature with respect to the phase of the surface temperature. Functions $T_n(\psi)$ are given by the expression (4). It follows from this that the intensity of radio emission from the moon oscillates periodically in the course of lunar cycles about some mean value which is generally termed the constant component of radio temperature.

Relationship (13) gives the brightness distribution along the lunar disk for any phase angle φ. Figure 7a represents a two-dimensional distribution of the effective temperature for a 0.8 cm wave, calculated from formula (13) for the phase angle $\varphi = 133^{\circ}$. Figure 7b corresponds to the analogous distribution obtained experimentally by A. Ye. Salomonovich (Ref. 9) with the use of a high-resolution radio telescope. It can be seen qualitatively that both distributions coincide and the decrease of the effective temperature towards the edge of the lunar disk is apparently caused by the increase of the reflection coefficient during tangential exit of the radiation. The theoretical curves of the distribution of lunar radio brightness, constructed in Reference 8 along the /601 equator and the meridian for a constant component, show a noticeable decrease of the intensity only towards the edge of the disk within the ring of 2-3 angular minutes. Note should be made that the radio temperature falls somewhat more rapidly along the meridian due to the latitudinal distribution of the surface temperature.

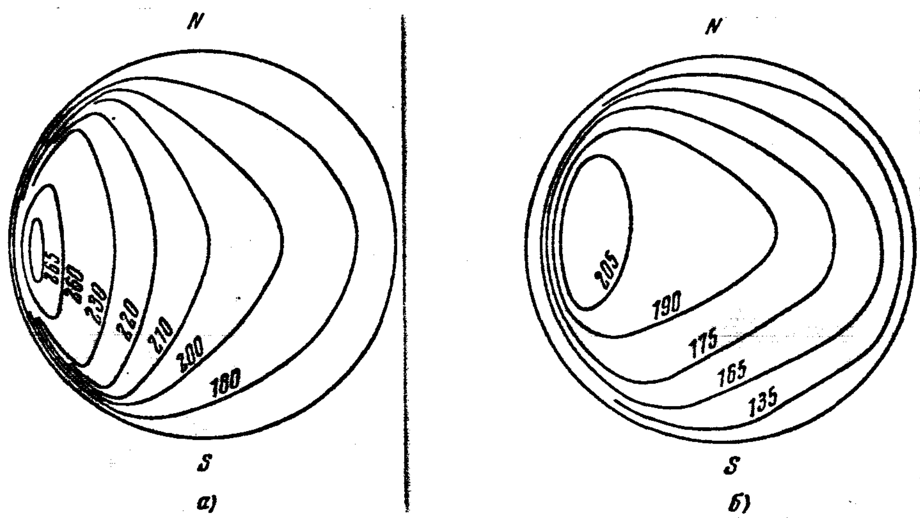

Figure 7. a) Effective temperature distribution over the lunar disk, calculated by formula (13) for a 0.8 cm wave. b) Analogous distribution obtained experimentally by A. Ye. Salomonovich (Ref. 9). The phase angle $\varphi = 133^{\circ}$; $\varphi = 0$ corresponds to full moon

In the specific case expression (13) for the center of the visible disk of the moon is significantly simplified:

$$T_e(0, 0, t) = (1 - R_{\perp}) \left\{ T_0(0) + \sum_{n=1}^{4} \frac{(-1)^{a_n} T_n(0)}{\sqrt{1 + 2\delta_n + 2\delta_n^2}} \cos(n\Phi - \varphi_n - \xi_n) \right\}, \qquad (14)$$

where

$$R_\perp = \left(\frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\right)^2$$

is the reflection coefficient during perpendicular incidence, and

$$\xi_n = \operatorname{arctg}\frac{\delta_n}{1+\delta_n}.$$

The harmonic amplitude higher than the first comprises a relatively small fraction of the first harmonic and as an approximation in many cases may be neglected. In such a case, oscillations of the radio emission from the center of the lunar disk may be approximately expressed by an extremely simple relationship

$$T_e(0,\,0,\,t) \approx (1-R_\perp)\left\{T_0(0)+\frac{T_1(0)}{\sqrt{1+2\delta_1+\delta_1^2}}\cos(\Phi-\varphi_1-\xi_1)\right\} \quad (15)$$

with sinusoidal variable component. It is apparent at a glance that the maximum of the lunar radio emission lags with respect to the full moon. The lag angle, equal to ξ_1, depends on the ratio $\delta = l_{\text{э}}/l_T$ of the penetration depth of the electromagnetic wave (or the thickness of the radio emitting layer) and the penetration depth of temperature wave. When $\delta \to \infty$, $\xi_1 \to 45^\circ$, and the amplitude of the variable component approaches 0. Physically this is quite obvious. The greater the thickness of the radio emitting layer the smaller the fraction of radiation which proceeds from the heated part, proportional to l_T. This leads to the decrease of the amplitude of radio temperature oscillations which results from the radiation of the layer l_T. Lagging also increases at the expense of an increasing lag of heating of the underlying layers. If radio emission took place from the surface itself, as is the case for infrared waves ($\delta \approx 0$), then the amplitude of oscillation of the first harmonic of radio temperature would be different from the true temperature of the surface T_1 (0) only by the coefficient, which is equal to emissivity $1 - R_T$. If the width of the diagram is such that radio emission is received from the whole lunar disk, then for interpretation of such measurements it is necessary to establish general relationships between the brightness distribution of radio temperature along the disk. In Reference 7, for the interpretation of experiments giving the mean temperature along the disk, relationships for brightness radio temperature were used which lead to errors. Approximate relationships for integral lunar radio emission were obtained in Reference 8, however, for interpretation and processing of precision measurements the accuracy of these relationships is insufficient. In Reference 11 accurate solutions were obtained for integral lunar radiation which corresponds to the increased accuracy of measurements.

According to Reference 8, the mean effective temperature is equal to

$$\overline{T}_e = \frac{1}{\pi} \int\int_{-\pi/2}^{+\pi/2} [1 - R(\varphi, \psi)] T_e(\varphi, \psi, t) \cos^2\psi \cos\varphi \, d\varphi \, d\psi. \quad (16)$$

It is worthwhile to view it as radiation of the center of the disk by introduction of the necessary conversion coefficients. /602

From formulae (15) and (16) after transformation and integration it is possible to obtain an expression for the mean effective temperature along the disk through the temperature of the center of the disk in the form

$$\overline{T}_e = (1 - R_\perp) \beta_0 T_0(0) + (1 - R_\perp) \sum_{n=1}^{4} (-1)^{\alpha_n} \frac{T_n(0) \beta_n}{\sqrt{1 + 2\delta_n + 2\delta_n^2}} \times$$
$$\times \cos(n\Phi - \varphi_n - \xi_n - \Delta\xi_n), \quad (17)$$

where

$$(1 - R_\perp) \beta_0 T_0(0) = \overline{T}_{e0}$$

is the constant component of the effective temperature averaged along the coordinates[1]

$$\frac{T_n(0) \beta_n}{\sqrt{1 + 2\delta_n + 2\delta_n^2}}$$

---

[1]$\overline{T}_{eo}$ may also be represented by the mean spherical emissivity $1 - \overline{R} = (1 - R_\perp)\,\alpha$ and through the constant component of the average surface temperature of the disk $\overline{T}_o = 0.964 T_o(0)$ as follows: $\overline{T}_{eo} = (1 - R_\perp)\,\alpha \times 0.964 T_o(0)$, where 0.964 is the averaging coefficient and α the mid-spherical emissivity normalized with respect to the center of the disk

$$\alpha = 1/\pi \, (1 - R_\perp) \int\int_{-\pi/2}^{+\pi/2} [1 - R(\varphi, \psi)] \cos^2\psi \cos\varphi \, d\varphi \, d\psi.$$

The dependence of α on dielectric constant is given in Reference 12.

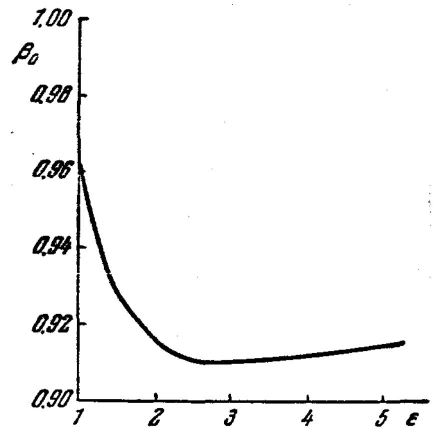

Figure 8. Coefficient β_0 as a function of ϵ.

is the n[th] harmonic of the effective temperature, averaged over the disk, β_0 and β_n are corresponding averaging coefficients and $\Delta\xi_n$ is the additional phase shift which occurs upon averaging.

Quantities β_0 and β_n are expressed in an extremely complex manner through integrals which depend on ϵ and δ of the lunar surface. Analytical calculation of these quantities is not possible and therefore in Reference 11 it was performed on an electronic computer for a broad interval of changes of ϵ and δ. Figure 8 shows the dependence of β_0 on ϵ. Figures 9 and 10 show coefficients β_1 and β_2 as a function of δ_1 for different values of ϵ.

It is apparent from Figure 9 that at constant δ_1 coefficient β_1 increases as ϵ decreases. This is associated with an increase of the oscillation amplitude of radio temperature near the edges of the lunar disk due to tangential radio emission from the surface. In reality the depth from which radio emission of a given point of the lunar surface takes place is equal to

$$l = l_0 \frac{1}{\sqrt{\varepsilon}} \sqrt{\varepsilon - \sin^2 r},$$

i.e., it decreases at the edge of the disk. Therefore, with decrease of ϵ the contribution to the total radio emission of areas located near the limb of the moon increases. Coefficients β_1 and β_2 for $\delta_1 > 10$ practically /603

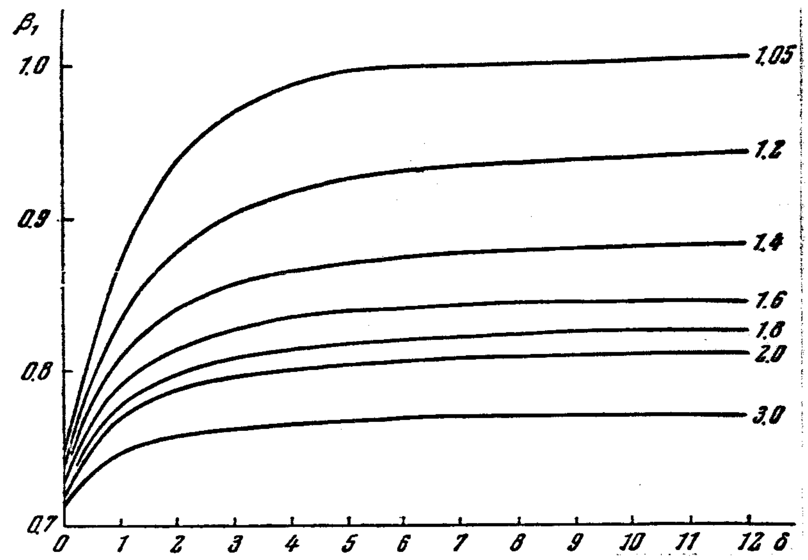

Figure 9. Coefficient β_1 as a function of δ_1 for different values of ϵ

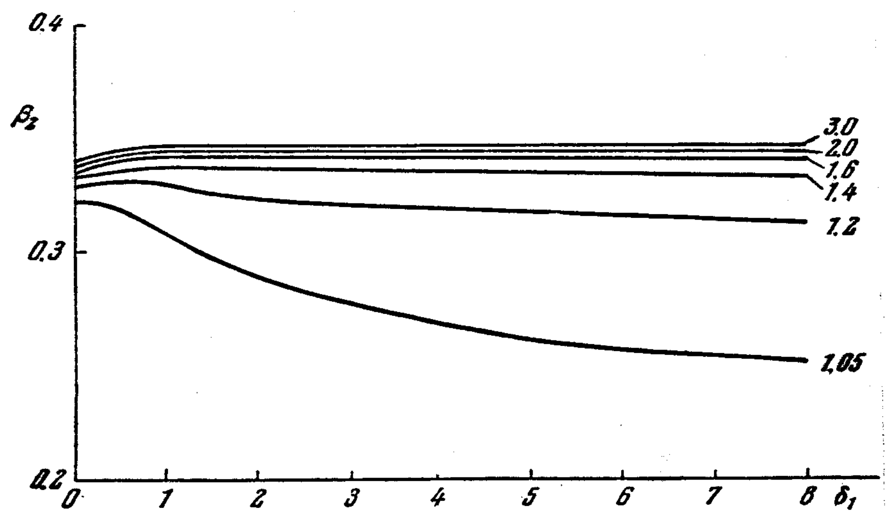

Figure 10. Coefficient β_2 as a function δ_1 ($\delta_2 = \sqrt{2\delta_1}$) for different values of ϵ

do not change with change of δ_1. Analyses, conducted in Reference 11, have shown that higher harmonics of the effective temperature averaged over the disk are significantly weaker as compared with corresponding harmonics of the effective temperature in the center of the disk. Thus, for a 0.4 cm wave the second harmonic amplitude of the mean effective temperature was 8 percent, and of the third - less than 1 percent of the first harmonic amplitude for the center of the disk, while for the center of the disk the corresponding magnitudes are 20 and 13 percent respectively. For longer wavelengths, and consequently for larger δ_n, higher /604

harmonics in the integral radio emission of the moon will be even weaker. This means that oscillations of the mean radio temperature along the disk are well described by the first harmonic alone. This is substantiated by the results of measurements of the integral lunar radio emission at different wavelengths.

Figures 11 and 12 show the phase relationships of the effective temperature with 0.4, 0.8, 1.6, 3.2 and 9.6 cm waves calculated from formulae (14) and (17) for the center and for the whole lunar disk (Ref. 11), which visually shows the smoothing effect which occurs with space averaging. The obtained values of conversion coefficients β_n from the /605

integral emission to the emission from the center of the disk and back permit the reduction of all the experimental data to one of the indicated characteristics.

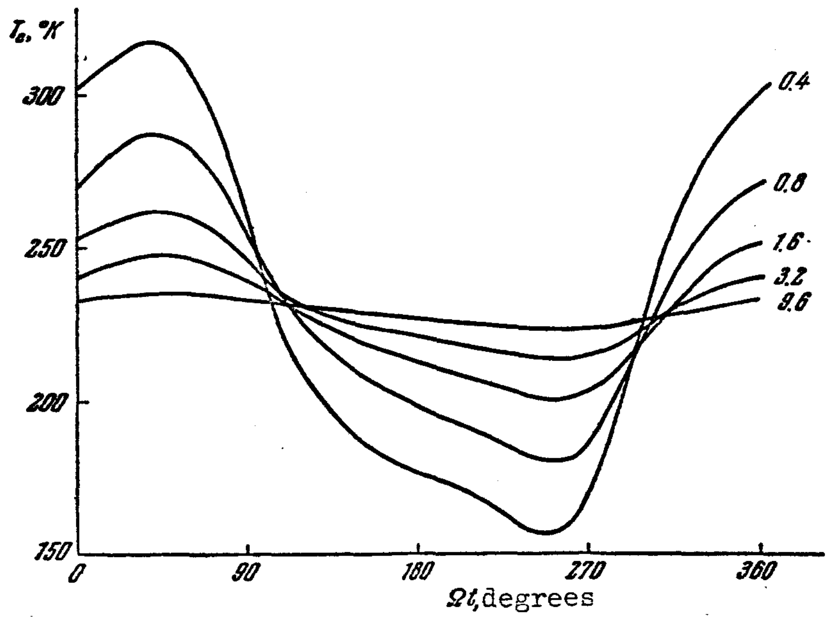

Figure 11. Phase dependence of the effective temperature of the center of the lunar disk for different values of λ

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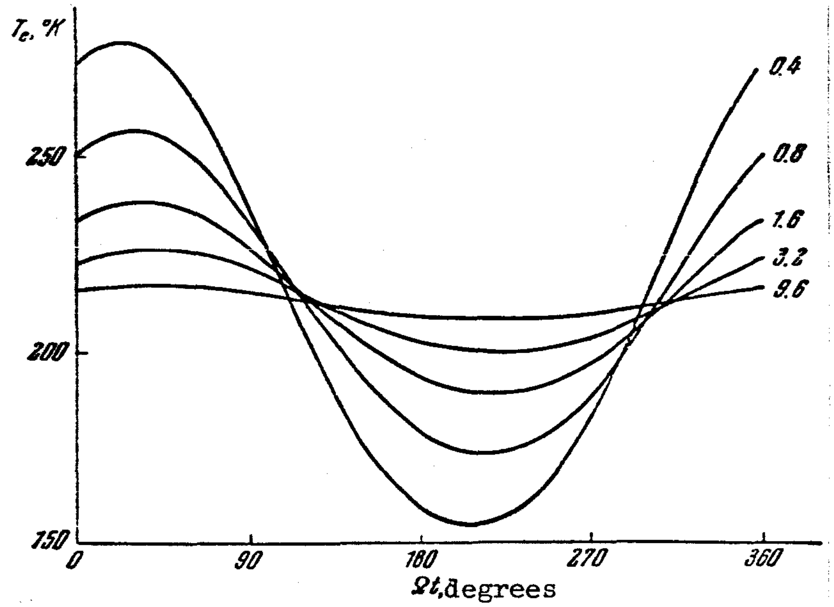

Figure 12. Phase dependence of the mean effective temperature over the lunar disk for different values of λ

Figure 13 shows the dependence of the additional phase shift $\Delta\xi$ for the first harmonic of the integral emission on δ_1. If ϵ changes within wide limits the maximum magnitude of $\Delta\xi$ does not exceed -5°. Consequently, the phase of the integral emission leads somewhat the phase of emission from the center of the disk. This is apparently associated with the effect of assymetrical heating of the lunar surface. An analogous phase shift for the second harmonic of the integral radiation is practically absent.

It is known experimentally that with up to 10 cm waves one can determine quite accurately the ratio of the constant component to the amplitude of the first harmonic,

$$M_{exp} = \frac{\overline{T}_e}{\overline{T}_{1e}}. \tag{18}$$

The comparison of this ratio with the theoretical value, which according to Reference 11 is equal to [1]

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[1] For the center of the moon $\beta_o/\beta_1 = 1$.

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$$M_{\text{theo}}=\frac{T_0(0)}{T_1(0)}\frac{\beta_0}{\beta_1}\sqrt{1+2\delta_1+2\delta_1^2}, \tag{19}$$

enables the determination of δ from the integral radio emission data.

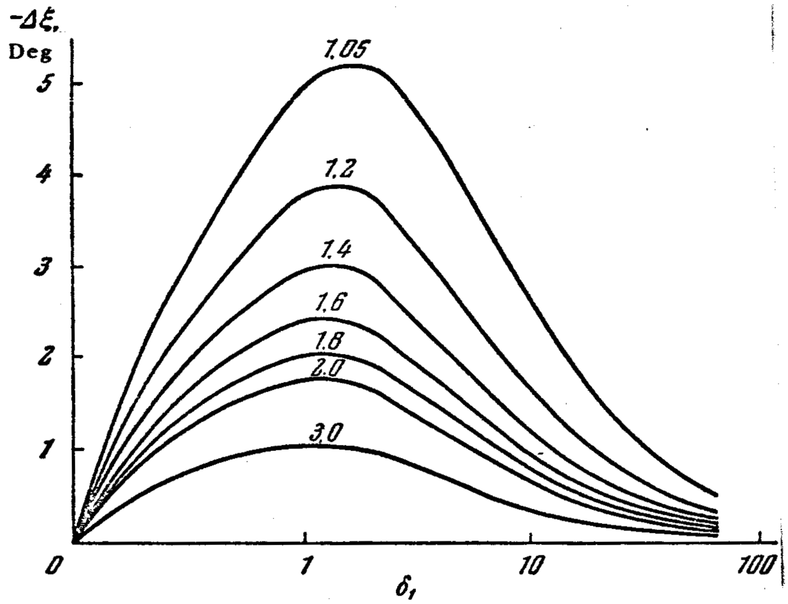

Figure 13. Additional phase shift as a function of δ_1 for different values of ϵ

In Reference 7, lunar radio emission was considered with an inhomogeneous model for the structure of the upper layer, when density and thermal properties change with depth. Since the calculations of radio emission of such a model in a general case are complex, a simplified, sharply inhomogeneous model has been accepted, according to which the solid thick layer of substance with parameter $\gamma \sim 100$-200 is covered with a thin layer of dust of the order of a few milimeters, for which $\gamma \approx 1000$. In addition it is assumed that this layer is absolutely transparent to centimeter and millimeter radio waves, i.e., the dense underlying layer is responsible for radio emission. It is apparent that in this case all of the obtained formulae for radio emission (13), (14), (15) are valid, but instead of the amplitudes of temperature harmonics on the very surface (i.e., on the dust layer), one should depict the values of temperature amplitudes on the surface of the underlying layer. The dust layer acts as thermal resistance, which decreases the amplitude of temperature oscillations below it by some factor m. In addition this layer causes a phase lag ξ_s of the temperature oscillations on the underlying layer as compared with the phase of oscillations of the surface temperature. /606

The radio emission of such a model for the center of the disk, neglecting higher harmonics, is described by the relationship

$$T_e=(1-R_\perp)T_0(0)+(1-R_\perp)\frac{T_1(0)}{m\sqrt{1+2\delta_1+2\delta_1^2}}\cos(\Phi-\varphi_1-\xi_1-\xi_s). \qquad (20)$$

The magnitude of weakening m and phase shift ξ_s of the temperature wave in the dust layer depends on its thickness and thermal conductivity. Both quantities are interrelated as follows

$$m=\sqrt{1+2\delta_s+2\delta_s^2} \text{ и } \xi_s=\operatorname{arctg}\frac{\delta_s}{1+\delta_s},$$

where δ_s is some auxiliary quantity, related to the parameters of dust layer by the relationship

$$\delta_s=\frac{k}{k'}\frac{\Delta y}{l_T}.$$

Here k' and Δy are thermal conductivity and the thickness of dust layer respectively and l_T is the penetration depth of the thermal wave in the subsurface layer. It is more convenient to express this quantity through the parameters γ and γ' for the underlying layer and for dust

$$\delta_s=\left(\frac{\gamma'}{\gamma}\right)^2\frac{\Delta y}{l_T}.$$

The dust layer which weakens the amplitude of the temperature wave by m = 1.45 times has $\delta_s = 0.4$. Taking as usual $\gamma' = 1000$ and $\gamma = 100$, and also $l_T \approx 25$ cm (see below), we obtain for the dust layer thickness $\Delta y = 1$ mm. In References 13 and 14 it was shown that if lunar matter is similar in chemical composition to terrestrial rocks, then the penetration depth of electromagnetic waves (or the thickness of the radio emitting layer) is proportional to the wavelength in a vacuum, i.e.,

(21)

where ã is a proportionality factor which depends on the properties of matter. In reality, for terrestrial dielectrics, if the tangent of the dielectric loss angle is much less than unity,

$$l_э=\tilde{a}\lambda, \qquad (22)$$

where σ is the effective electrical conductivity at a given frequency,

$$\operatorname{tg}\Delta=\frac{2\sigma}{\varepsilon f}$$

is the dielectric loss angle, f is frequency of the wave and v is the velocity of light in a vacuum. It will become clear later that equation (21) is valid also for lunar rocks (Refs. 3, 13, 14, 34). Thus the longer the wavelength of radio emission, the greater the depth which is responsible for its origination. /607

In this connection, if, as in the case of the earth, the temperature in the interior of the moon increases due to the heat flux from the interior, then the constant component of radio emission must increase with the wavelength. In References 15 and 16 theoretical analyses are given for the effect of internal thermal flux on the lunar radio temperature.

In Reference 16, for calculation purposes it was assumed that in a thick layer, compression of substance is possible into the depth, and consequently the thermal conductivity may be a function of y. Here, however, for simplicity of calculation, damping of electromagnetic waves was considered independent of y.

The constant component of temperature at a depth y in the presence of internal heat flux is a function of y and in the general case it equals

$$T_0(\varphi,\psi,y)=T_0(\varphi,\psi)+t(y), \tag{23}$$

where T_0 (φ, ψ) is a constant temperature component, resulting from solar heat and defined in Section 2, t(y) is an additional temperature, determined by the density of thermal flux q_s from the interior of the moon and by thermal conductivity k(y), and t(0) = 0, and

$$t(y)=q_s\int_0^y\frac{dy}{k(y)}. \tag{24}$$

In Reference 16 it is assumed that $T(y, \varphi, \psi)$ differs little from the following linear function along variable y

$$T(y,\varphi,\psi)=T_0(\varphi,\psi)+by+gy^2. \tag{25}$$

According to (11) and (25) the following expression is obtained for the constant component of the effective temperature for a surface element:

(26)

For the center of the disk cos r' = 1 and

$$T_{e\lambda}(0,\ 0)=(1-R_{\perp})(T_0(0,\ 0)+bl_э+2gl_э^2). \tag{27}$$

It can be seen from (21) and from the obtained expression, that as the wavelength increases one should observe the increase of radio brightness of the central part of the disk, while the edges of the disk, where cos r' ≈ 0, have a constant radio brightness. Neglecting the quadratic term and considering that for the moon coefficient $\tilde{a} = 2l_T^3$, we obtain an expression for the internal temperature gradient for the moon by measuring on two wavelengths the constant components of the effective temperature

$$\operatorname{grad} T=\frac{T_{e\lambda_2}-T_{e\lambda_1}}{(1-R_{\perp})\,2l_T\,(\lambda_2-\lambda_1)}\,. \tag{28}$$

Multiplying (28) by the thermal conductivity coefficient and making the necessary transformations we obtain the following expression for the thermal flux:

$$q=\frac{(T_{e\lambda_2}-T_{e\lambda_1})\sqrt{\frac{\Omega}{2}}}{(1-R_{\perp})\,2\gamma\,(\lambda_2-\lambda_1)}\,. \tag{29}$$

The relationships (28) and (29), defined in Reference 16, enable calculation of the temperature gradient and of thermal flux from the experimental data. /608

The question of polarization of lunar radio emission presents a certain interest. Polarization of radiation from a surface element is associated with a different emissivity of the surface for horizontally and vertically polarized radiation, and its calculation is quite elementary. The problem of polarization of integral radiation is more complex. In Reference 8 there are pertinent calculations made, and it is shown that integral radiation is polarized only as a result of latitudinal changes of temperature of the lunar surface. The degree of polarization depends on the dielectric constant and does not exceed 1-2 percent. In Reference 8, a qualitative discussion is given in geometrical-optical approximation regarding the possible effect of coarseness on the intensity of radio emission. Now this problem requires rigorous solution. The investigation of the effect of coarseness on radio emission polarization for surface elements as well as for the whole lunar disk is extremely important.

4. Experimental Data on Lunar Radio Emission

Lunar radio emission was first measured by Dicke and Beringer in 1946 on a 1.25 cm wave (Ref. 18). They made only single measurements in the proximity of the full moon (phase angle +18°). The first systematic observations of lunar radio emissions in the course of the whole lunar cycle were conducted in 1949 by Piddington and Minnett (Ref. 7) on a 1.25 cm band. It was discovered that the average effective temperature over the lunar disk on this wavelength changes approximately sinusoidally according to the equation $T_e = 215^{\circ} + 36 \cos (\Phi - 45^{\circ})$. An interesting characteristic of the obtained results is the fact that the amplitude of these changes is about 4 times smaller than the amplitude in infrared wavelengths, and the maximum of radio emission lags with respect to the optical phase by approximately 45° (for infrared radiation, lag is practically absent). These authors found the correct explanation for this phenomenon in that radio waves originate also from the subsurface layers, where the temperature changes are smaller than on the surface and temperature wave phase lag takes place. In 1952 measurements were conducted at NIRFI of lunar radio emission on a 3.2 cm wavelength (Ref. 13). In this work only the upper limit for the magnitude of the relative change of the effective temperature was established which is ≤ 7 percent, with the mean temperature value being 170°K. Later measurements, conducted in 1959-1961 on a 3.2 cm wavelength (Refs. 22, 37) enabled the discovery of phase relationship of lunar radio emission on the same wavelength.

In 1958 A. Ye. Salomonovich discovered the phase change of radio temperature on an 8 mm wave (Ref. 32). From the first experimental works it followed that the variable part of lunar radio emission depends significantly on wavelength, which enabled the establishment of the validity of equation (21) for the moon (Refs. 13, 14).

In recent years a large amount of experimental material has been accumulated on lunar radio emission in the 0.13-168 cm wavelength region. The results of these measurements are given in Table 2. The first column indicates the wavelength; the second - diameter of aerial; the third - the width of the directivity diagram and finally the fourth, fifth and sixth columns give values of the constant component T_{oe}, amplitude of the first harmonic of radio temperature oscillations T_{1e} and its phase lag ξ_1, respectively. Thus almost all experimental data (with the exception of data obtained in the millimeter wavelength range at a large radio telescope resolving power) are approximated in the form

$$T_e = T_{0e} + T_{1e} \cos (\Phi - \xi_1).$$

Table 2 gives the magnitudes of measurement errors, which are given by the authors, as well as the value of δ_1 and δ_1/λ, calculated from the /609

table data. The table contains measurements made by ordinary methods, giving an accuracy of ±10-±20 percent, as well as precision measurements with an accuracy of ±2 - 3 percent. The first type of measurement comprises a group of relative measurements and the second type is absolute. In the relative measurement group the discrepancies between the values obtained by different authors even on the same wavelength (disregarding definitely erroneous measurements, Refs. 41, 42) reach twice the value of tolerance given by each author, i.e., 30 percent. In the precise group of measurements, discrepancies on each wavelength are much smaller than the tolerance of each measurement.

For relative measurements of the oscillations of intensity, measurements on different wavelengths are interesting. They are performed by the same method and by the same authors. In this connection it is in order to point out the results obtained in 1959-1961 by a group of radio astronomers at FIAN on the 0.8, 2.0, 3.2 and 9.6 cm wavelengths, using a 22 m radio telescope (Refs. 20-23). The high resolving power of this radio telescope enabled these authors to obtain the two dimensional brightness distribution over the lunar disk as a function of its phase on the 0.8, 2.0 and 3.2 cm waves, and to discover the theoretically (Ref. 8) predicted darkening of the edge of the lunar disk, resulting from different emissivity. The precise group of measurements includes data obtained at NIRFI by the "artificial moon" method on the 0.4, 1.6, 3.2, 9.6, 32.3, 35, 36 and 50 cm wavelengths (Refs. 24, 30, 35, 36, 38, 40, 50, 52, 53). These measurements enabled determination of thermal parameters of the substance of the upper lunar crust, its density and dielectric constant as well as systematic increase of the lunar temperature with an increase of wavelength. For the first time the phase relationship of radio emission was discovered and measured on the 9.6 cm wavelength. Here it is appropriate to stress the importance of the first detailed measurements of lunar radio emission on the 0.13 and 0.18 cm waves, conducted at NIRFI by L. N. Fedoseyev (Ref. 25) and A. I. Naumov (Ref. 26). Until recently there were no detailed measurements made; if one disregards the single measurements of Sinton on a 0.15 wavelength, using optical techniques.

5. Structure of the Lunar Crust

Presently, there exist different hypotheses regarding the structure of the upper crust of the moon. A widespread hypothesis, especially abroad, is the solid dust layer proposed by Gold (Ref. 55). According to this hypothesis, the ultraviolet and corpuscular radiation of the sun destroys the crystalline lattice of minerals, meteoritic impacts break up and mix the basic lunar rocks, as a result of which a fine dust occurs.

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Table 2. Summary of Experimental Results on Lunar Radio Emission

Ordinal number	λ, om	Dia. of mirror d, m	Half-width of diagram, θ	T_{e0}, °K	T_1, °K	ξ, deg.	Measurement of error, %	$M=\frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
1	0.13	0.42	10'	219	120	16	±15	1.82	0.22	1.7	1963	L.N. Fedoseyev (NIRFI)[25]	Isolated measurements using optical techniques
2	0.15										1955	W. Winton[27]	
3	0.18	1	6'	240	115	14	±20	2.08	0.34	1.9	1963	A.I. Naumov (NIRFI)[26]	
4	0.40	0.95	25'	230	73	24	±10	3.15	0.9	2.20	1961	A.G. Koslyakov (NIRFI)[28]	
5	0.40	22	1.6'	228	85	27	±15	2.7	0.76	1.7	1963	A.G. Koslyakov, A.Ye. Salomonovich (NIRFI, FIAN)[29]	
6	0.40	0.5	36'	204	56	23	± 4	3.8	0.95	2.3	1963	A.G. Kislyakov, V.M. Plechkov (NIRFI)[30]	
7	0.43	3.5	6.3'				±20				1958	R. Coates[31]	Three measurements for phases 77, 126 and 280° (ϕ = 0 corresponds to new moon), T_e are 182, 243 and 245°K respectively.
8	0.8	2	18'	197	32	40	±10	6.16	1.84	2.3	1958	A.Ye. Salomonovich (FIAN)[32]	
9	0.8	22	2'	211	40	30	±15	5.28	1.95	2.4	1962	A.Ye. Salomonovich B.Ya. Losovskiy (FIAN)[20]	

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Table 2 (Continued)

Ordinal number	λ, om	Dia. of mirror d, m	Half-width of diagram, θ	T_{e0}, °K	T_1, °K	ξ, deg.	Measurement of error, %	$M = \frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
10 11	0.86 1.25		12'	180	35	35	±15	5.14	1.88	2.18	1958	R. Dicke, R. Beringer[18]	An isolated measurement: phase + 18°, T_e = 270°K.
12	1.25	1.12	45'	215	36	45	±10	6	2.1	1.7	1949	J. Piddington, H. Minnett[7]	
13	1.63	4	26'	224	36	40	±10–15	6.22	2.4	1.5	1959	M.R. Zelinskaya, V.S. Troitskiy, L.N. Fedoseyev (NIRFI)[34]	
14	1.63	1.5	44'	208	37	30	± 3	5.6	2.2	1.3	1962	S.A. Kamenskaya, B.I. Semenov, V.S. Troitskiy, V.M. Plechkov (NIRFI)[35]	
15	1.63	1.5	44'	207	32	10	± 3	6.62	2.25	1.4	1963	D.A. Dmitriyenko, S.A. Kamenskaya (NIRFI)[36]	
16	2.0	22	4	190	20	40	±75	9.5	4.0	2.0	1961	A.Ye. Salomonovich V.I. Koshchenko (FIAN)[20]	
17	2.3		2' × 40'			35					1961	N.L. Kaydanovskiy V.N. Iskhanova, G.P. Apushinskiy, O.N. Shivris (GAO)[81]	The phase shift was obtained for the displacement of the center of gravity of radiation.
18	3.2	22	6'	223	17	45	±15	13.1	5.3	1.7	1961	V.N. Koshchenko, B.Ya. Losovskiy, A.Ye. Salomonovich (FIAN)[22]	

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Table 2 (Continued)

Ordinal number	λ, om	Dia. of mirror d, m	Half-width of diagram θ	T_{e0}, °K	T_1, °K	ξ, deg.	Measurement of error, %	$M=\frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
19	3.15	15	9'	195	12	44	±15	16.2	6.6	2.1		G. Mayer, R. McCullough, R. Slonaker[19]	
20	3.2	4	35'	170	12		±15	14	60	1.9	1955	M.R. Zelinskaya, V.S. Troitskiy (NIRFI)[13]	
21	3.2	4	40'	255	16	50	±15	15.9	6.43	2.05	1961	K.M. Strezhneva, V.S. Troitskiy (NIRFI)[37]	
22	3.2	1.5	1°12'	210	13.5	55	± 2.5	15.55	6.35	2.0	1961	V.D. Krotikov, V.A. Porfir'yev, V.S. Troitskiy (NIRFI)[24]	
23	3.2	1.5	1°27'	213	14	26	± 2	15.2	6.2	1.95	1962	L.N. Bondar', M.R. Zelinskaya, V.A. Profir'yev, K.M. Strezhneva (NIRFI)[38]	
24	3.2	4	40'	216	16	15	± 3	13.5	5.4	1.7	1962		
25	9.4	3.5	2°20'	220	5.5	–	± 5	40	19.5	2	1961	W. Medd, N. Broen[39]	The data were recalculated for the center of the visible disk.
26	9.6	22	19'	230			±15	46	21	2.3	1961	V.N. Koshchenko, A.D. Kuz'min, A.Ye. Salomonovich (FIAN)[23]	
27	9.6	4	1°40'	218	7	40	± 2.5	31	13.4	1.4	1961	V.D. Krotikov (NIRFI)[40]	

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Table 2 (Continued)

Ordinal number	λ, om	Dia. of mirror d, m	Half-width of diagram, θ	T_{e0}, °K	T_1, °K	ξ, deg.	Measurement of error, %	$M=\frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
28	10			215							1951	J. Piddington, H. Minnett[17]	Single measurement.
29	10			130							1956	N.L. Kaydanovskiy, M.T. Tursubekov, S.E. Khaykin (GAO)[41]	
30	10	10		315	75						1955	K. Acabae[42]	
31	10.0	25	18'	256			±15				1960	J. Castelly, C. Ferioli, J. Aarons[43]	Observation in the course of one day (50 recordings of the moon).
32	10.3										1961	J. Waak[45]	Phase change of order of ~ 2.5% is reported but numerical data are not given.
33	10.3	25	18.5'	207			±15					R. Slonaker[44]	Unpublished reference in[77]
34	11	25	17'	214			±12				1960	P. Messger, H. Strassl[46]	Some temperature change is observed near the new moon.
35	20.8	25	36'	205	5						1961	J. Waak[45]	Phase change is reported of the order of 2.5%.
36	21	25	35'	250	≤5		±15				1959	R. Messger, H. Strassl[47]	

Table 2 (Continued)

Ordinal number	λ, om	Dia. of mirror d, m	Half-width of diagram, θ	T_{e0}, °K	T_1, °K	ξ, deg.	Measurement of error, %	$M=\frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
37	22	76	15'	270			±20				1960	R. Davies, R. Jennisson[48]	
38	22			270							1958	G. Westerhout[49]	
39	23	25	38'	254	≤6.5		±15				1960	J. Castelly, C. Ferioli, J. Aarons[43]	
40	32.3	8	3°	233			± 2.5				1963	V.A. Razin, V.T. Fedorov (NIRFI)[50]	
41	33			208								J. Dennisse, E. de Roux[51]	Not published, reference in [54].
42	35	8	3°6'	236			± 4				1963	V.D. Krotikov, V.A. Porfir'yev (NIRFI)[52]	
43	36	8	3°10'	237			± 3				1963		
44	50	8	4°40'	241			± 5					V.D. Krotikov (NIRFI)[53]	
45	75	25	2°	185			±20				1957	S. Seeger, G. Westerhout, R. G. Conway[54]	
46	168		13.6'× 4.6°	233			± 4				1961	J. Baldwin[15]	

The depth of dust may reach several kilometers. This continuous dust layer does not remain at the place of its formation but is transferred from higher elevations onto the lowlands.

In many works, which discuss the nature of the lunar surface, the thought is expressed that since there is no weather on the moon, then the lunar surface is a fresh, unchanged surface of magnetic rock (see, for example, Reference 56).

Examining the nature and the structure of the lunar surface on the basis of comparison of the optical characteristics of the lunar surface (reflection coefficient, scattering factor, color, etc.) with terrestrial rocks leads to the conclusion that the lunar surface is not a fresh solid /614
rock. Comparison indicates the slag nature of the surface. From here N. N. Sytinskaya proposed the so-called meteor-slag hypothesis for the formation of the upper layer of the moon (Ref. 57). According to this hypothesis the lunar crust, down to a depth of possibly several meters, is meteor debris, which results from the breaking up and mixing and volatilization of rock by meteors. Condensation of vapors and cooling of molten rock under vacuum leads to porous formations resembling slag.

The above-mentioned hypotheses in any case treat the lunar surface as being uniform in depth, and having no sharp structural changes of the substance near the surface. During the interpretation of Pettit's experimental results on measurement of the lunar surface temperature during eclipse, Wesselink (Ref. 1) also used the concept regarding homogeneous structure of the lunar surface. Wesselink has shown that the experimental curve of the change of temperature of the lunar surface during an eclipse coincides with the theoretical curve, calculated for a homogeneous model with $\gamma = (k\rho c)^{-1/2} \approx 1000$.

Later, however, Piddington and Minnett (Ref. 7), while explaining their experimental results on lunar radio emission came to the conclusion that the surface of the moon has a thin layer of dust (several millimeters in thickness) which is transparent to radio waves, but which significantly weakens the thermal wave. The presence of the thin layer of dust explained the presence of a significant phase shift of radio emission with respect to the heating phase. The explanation was more satisfactory than follows from the uniform lunar surface structure concept.

Jaeger and Harper (Ref. 59), interpreting the results of Pettit indicated that the experimental curve for cooling of the lunar surface during full umbra proceeds somewhat later than follows from the homogeneous structure of the lunar surface concept. On the basis of conducted calculations they came to the conclusion that the two-layer model for the lunar surface, according to which the presence of thermally nonconductive layer of dust 2-3 mm in thickness is proposed with thermal parameter γ = 1000, lying on a solid subsurface layer with γ = 100, gives better agreement with experimental data than the homogeneous model. Thus, the concept of a two-layer structure of the lunar surface originated. What is its structure? Can the upper layer be considered homogeneous or does it have a sharply inhomogeneous structure?

These questions were dealt with in Reference 3, in which analysis of specially conducted measurements at NIRFI of lunar radio emission in the 0.4-3.2 cm range is presented. This work also includes the other available literature data. This analysis is based on the comparison of experimental data on the dependence of lunar radio emission characteristics (quantities M (λ) and ξ (λ)) on wavelength with theoretical data for homogeneous and for two-layer structure models according to the formulae of Section 3.

The physical possibility of discovering the sharp inhomogeneity of the layer (two-layer structure) by comparison of different wavelength data is associated with the fact that different wavelength data correspond to temperature measurement at different depths. Any sharp changes of properties of the upper layer as a function of depth lead to a change of temperature distribution and may be found in radio emission. In the case of constant temperature with time and with depth, radio emission will not uncover any inhomogeneities. Therefore investigation of the upper layer of the lunar surface (in the absence of thermal flux from the interior) is possible only to a depth which is comparable to the depth where thermal oscillations still take place, i.e., down to $(3\text{-}4)l_T$. It will be shown

later, however, that due to significant thermal flux from the interior of the moon it is possible to investigate layers to significant depths. Study of this layer is most accessible because in the upper layer of $(3\text{-}4)l_T$ thickness temperature gradients from solar heat are great. /615

From the indicated principal characteristics of lunar radio emission the most accurately determinable is the relative magnitude of the amplitude of radio temperature oscillations. In the case of a homogeneous layer the radio emission of the shorter wavelength is determined by a thinner layer and in the limit $\lambda \to 0$ will be emanating from the surface. The amplitude of oscillation of radio temperature (in the case of the absolute black body conditions of the surface) will, in theory, be equal to the amplitude of temperature oscillations on the very surface, i.e., about 155^o. For a two-layer structure the amplitude of oscillations of radio temperature with a shortening of wavelength (as long as the dust layer remains transparent) will approach the amplitude of oscillation of temperature under the dust layer, i.e., m times smaller than the magnitude for a homogeneous layer. This in fact enables the discovery of a sharp discontinuity, which is the layer of nonabsorbing dust in the case of a two-layer model. For this purpose, in Reference 3, an experimental curve was constructed for the dependence of the ratio of M (λ), the constant component, to the amplitude of the variable as a function of λ. The relationship M (λ) can be determined with great accuracy since it is independent of the accuracy of absolute measurements and the emissivity of the moon. Figure 14 shows this curve augmented with the results of the latest measurements of λ = 0.13 cm and λ = 0.18 cm. It is clearly seen that extrapolation of the curve to $\lambda \to 0$ gives the ratio of the constant component of the surface temperature to the amplitude of the first harmonic on the surface

$$M(0) \cong \frac{T_0(0)}{T_1(0)}.$$

This ratio is equal to

$$\frac{T_0}{T_1} = 1.5. \tag{30}$$

The theoretical curve M (λ) for the two-layer model according to equation (20) has the form

$$\left.\begin{aligned} M(\lambda) &= m\frac{T_0(0)}{T_1(0)}\sqrt{1+2\delta_1+2\delta_1^2}, \\ l_9 &= a\lambda. \end{aligned}\right\} \tag{31}$$

At m = 1 a function is obtained for a single-layer model. The theoretical function M (λ) (solid curve) passes through the experimental points only at m = 1 and $\delta = 2\lambda$, i.e., for a single-layer model. In Figure 14 the dotted line also shows theoretical curves for a two-layer model with a dust layer which weakens the amplitude of temperature oscillations under it by m = 1.5 times. During extrapolation to $\lambda \to 0$ these curves, according to the above discussion, must approach the large value of M(0), /616 equal to $\frac{T_e(0)}{T_1(0)}$ m. Both of the indicated theoretical curves correspond to different values of the coefficient ã, i.e., to different electrical properties of the medium. It should be noted that in reality no matter how transparent the layer of dust is, still for some wavelengths it will become opaque. Consideration of this must be manifest in the fact that starting from this wavelength curves M (λ) at $\lambda \to 0$ will converge to the point $m_s = 1$, as shown in Figure 14 by the dotted part of the broken line curves. In general, for any two-layer model with given m and different assumptions about the value of ã a beam of straight lines will be obtained which originate from the point m $\frac{T_o(0)}{T_1(0)}$ on axis M (λ). It is

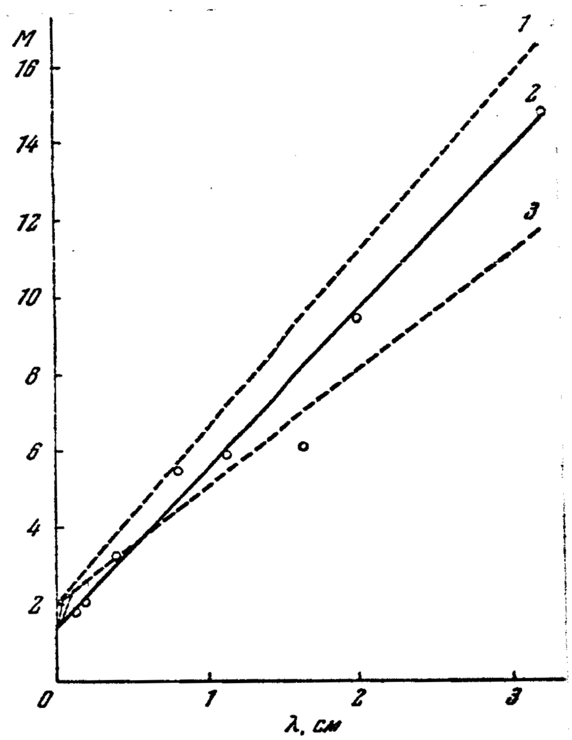

Figure 14. M as a function of λ. Curve 2 corresponds to a single-layer model with $m_s = 1$, $\delta_1 = 2\lambda$. Curve 1 corresponds to a two-layer model with $m_s = 1.5$, $\delta = 1.5\ \lambda$. Curve 3 with $m_s = 1.5$, $\delta = \lambda$

apparent from Figure 14 that it is possible to select such a theoretical line which would correspond to a two-layer model and which would coincide with experimental results on one or on closely spaced wavelengths. However, in this case experimental points lie on the curve which corresponds to different values of coefficient $\bar{a}$. This means that the electrical properties of the lunar surface depend on the wavelength in an incomprehensibly complex manner.

Thus, the analysis of the dependence of amplitude of radio temperature oscillations on wavelength uniformly support the homogeneous structure of the upper crust. In order to determine the model in Reference 3 analyses of experimental data were conducted on the basis of the relationship of the phase lag of radio emission ξ to quantity M. The quantities ξ and M are interrelated and depend on the wavelength. The nature of their dependence is determined by the structure of the lunar surface. In order to answer the question as to which form of surface structure is supported by the experimental data it is necessary to construct theoretical curves for ξ (M) on the ξ and M plane, which would correspond to both models, and to plot experimental points on the same graph. The theoretical value of M (λ) is given by the relationship (31) and the corresponding phase shift by

$$\xi = \operatorname{arctg}\frac{\delta_1}{1+\delta_1} + \xi_s, \tag{32}$$

where ξ_s is the phase shift which occurs in the dust layer (for a uniform surface structure $\xi_s = 0$). The theoretical relationship ξ (M) is obtained by elimination of the quantity δ_1 from (31) and (32) and, according to Reference 3, has the following form:

$$\xi(M) = \operatorname{arctg}\frac{-\frac{1}{2}+\sqrt{\frac{1}{4}+\frac{1}{2}\left\{\left[\frac{M}{m_s}\frac{T_1(0)}{T_0(0)}\right]^2-1\right\}}}{\frac{1}{2}+\sqrt{\frac{1}{4}+\frac{1}{2}\left\{\left[\frac{M}{m_s}\frac{T_1(0)}{T_0(0)}\right]^2-1\right\}}} + \xi_s. \tag{33}$$

Figure 15 shows curves calculated from formula (33) in the construction of which the following ratio was accepted

$$\frac{T_0(0)}{T_1(0)} = 1.5,$$

which follows from the experimental data. Curve 1 corresponds to a homogeneous structure of the lunar surface with $m_s = 1$ and $\xi_s = 0$. Curve 2 corresponds to a two-layer model with an extremely thin layer of dust, $m_s = 1.1$ and $\xi_s = 5^\circ$. When the layer is thickened to $m_s = 1.4$ and $\xi_s = 15^\circ$ we obtain curve 3. The experimental points are plotted as circles with designation of limits of possible errors for ξ and M. Each point corresponds to the mean values of ξ and M obtained for each wavelength on the basis of Table 2. /617

As is apparent from Figure 15 the experimental points[1] all together correspond to curve 1, calculated for a one-layer model and all cannot at the same time be in agreement with the two-layer model, which even

[1]In comparison with the figure in Reference 3 experimental points are plotted of recent measurements on λ = 0.13 cm (Ref. 25) and 0.18 cm (Ref. 26).

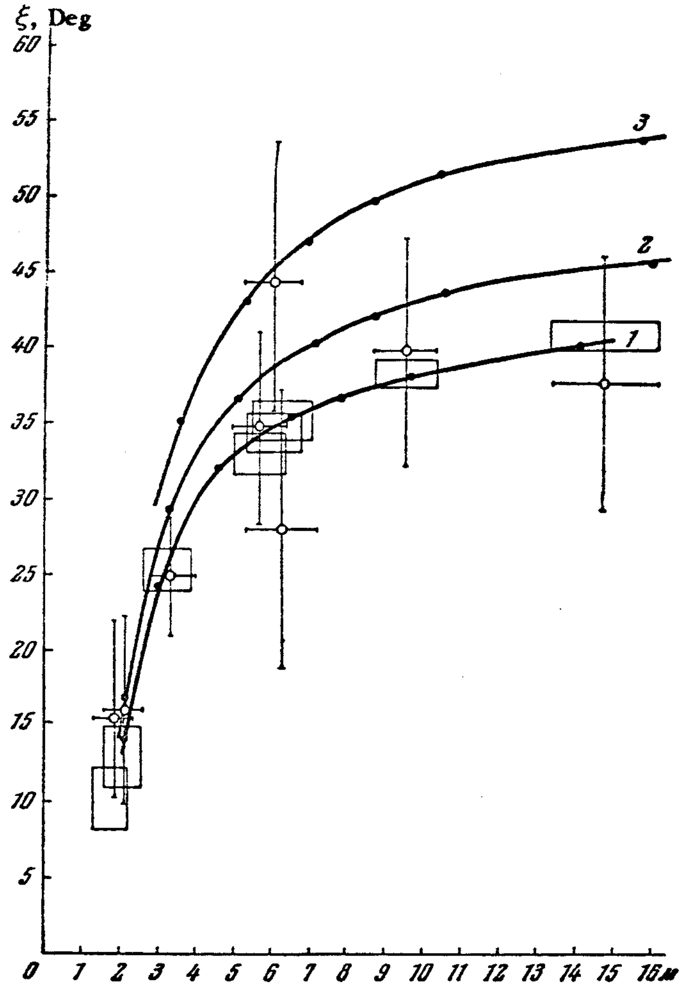

Figure 15. A theoretical dependence of the lag of the first harmonic of lunar radio emission on the ratio of constant component to the amplitude of the first harmonic. 1 - homogeneous surface structure ($m_s = 1$; $\xi_s = 0$; $\delta = 2\lambda$); 2-3 - two-layer dust model ($m_s = 1.1$; $\xi_s = 5^{\circ}$; $\delta = 2\lambda$ and $m_s = 1.4$; $\xi_s = 15^{\circ}$; $\delta = 1.5\lambda$). Black dots are theoreticals for the following wavelengths: 0.13; 0.4; 0.8; 1.25; 1.63; 2.0 and 3.2 cm. Circles are experimental points, plotted with indication of the uncertainty in values of ξ and M. Rectangles correspond to errors of ξ and M if ξ is calculated from the value of ξ_1, determined from the experimental data

has a very thin layer of dust (curve 2). In reality, if the point which corresponds to the measurement on a 1.25 cm wave can be made to agree /618 with the two-layer model (curve 3), then data for other wavelengths do not fall on this curve. If on a 3.2cm wave the theoretical value of phase $\xi = 45^{\circ}$ for a two-layer model with a very thin dust layer is within the limits of possible errors, then on the 0.4 and 1.6 cm waves theoretical values of phase differ from the experimental. It is possible to select two-layer model parameters in such a way as to satisfy experimental data for one or for closely lying wavelengths, but it is not possible to do it throughout the whole wavelength interval. In order to achieve the coincidence of experimental data with theoretical relationships for a two-layer model, it is necessary to decrease the thickness of the layer even less than in curve 2, and this means that the dust layer which is transparent to the utilized wavelengths is absent from the surface of the moon.

Consequently, a unified agreement follows that down to the depth of penetration of 3.2 cm waves, i.e., 1-2 m, the upper crust of the moon has an approximately homogeneous structure, and the two layer, sharply discontinuous, dust model does not correspond to reality[1]. Therefore, instead of the insufficiently accurately measureable quantity ξ_{exp} it is possible to utilize its theoretical value from the experimentally determined quantity M. In Figure 15 these values (rectangles) fall accurately on the curve which corresponds to the homogeneous structure of the lunar surface. Another important result of the analysis in Reference 3 is the establishment of a quantitative relationship between the wavelength λ and the quantity $l_э$. See formula (21)

$$\delta = 2\lambda, \quad l_э = 2\lambda l_T, \tag{34}$$

which is valid with consideration of new data, in the 0.1-3.2 cm range. Figure 16 gives values of ξ/λ as a function of λ, averaged for each wavelength from all available data. Some deviations from the indicated dependence are obtained in the region of 1.63 cm waves. It may be interpreted as the presence of absorption by the lunar substance at this wavelength. Other explanations may also be given. But to explain the nature of this effect it is necessary to conduct additional measurements on wavelengths which are close to this line.

The investigation of the structural model of the upper layer from /619 the nature of the lunar radio emission spectrum, conducted in Reference 3

[1]In Section 9, on the basis of analysis of the relationship between constant radio temperature component and wavelength, it is shown that the upper lunar layer is approximately homogeneous down to the depth of 15-20 m.

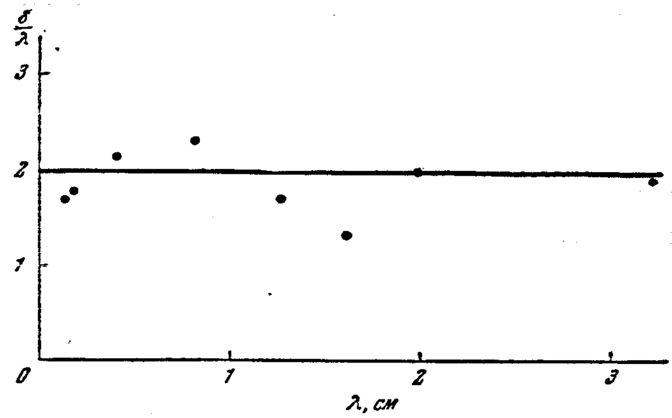

Figure 16. The ratio δ/λ as a function of wavelength λ. Black dots correspond to experimental data

is so far the only one, but other works dealing with the analysis of data on a given wavelength often make conclusions regarding the structural model. Here in our country, the works indicate most frequently the validity of a single-layer model, which is established on the basis of the relationship between the amplitude of a variable part and the phase lag, which is characteristic for a single-layer model (see for example References 9, 32).

In foreign works analogous characteristic remarks are made, not in regard to a single layer, but to a two-layer dust model (see for example Reference 60). However, analyses of radio emission are not performed in a broad range of wavelengths.

Article 61 discusses experimental work on radio emission and radar probing of the moon within the framework of a homogeneous model of its structure. The author considers the lunar surface to be covered with a layer of dusty material, the thickness of which may differ in the valleys and on the hills. However, he gives no new quantitative data.

Some broader discussion regarding the structure of the upper layer of the moon was given in the work of Gibson (Ref. 62), on the basis of data obtained by investigation of lunar radio emission during an eclipse $\lambda = 0.86$ cm. This author did not discover any drop of intensity exceeding the fluctuation of the output signal, which comprised one degree. Knowing the depth of the layer which cools during an eclipse and taking the radio temperature drop by 1°, Gibson found the magnitude of the absorption coefficient of the substance in the cooling layer. The absorption coefficient was found to be 10 times less than that determined from radio temperature measurements during lunation on the same wavelength. Such a discrepancy is explained by the author as being caused by the

existence of a two-layer structure of the lunar surface. The first layer with low thermal conductivity (γ = 1000) is responsible for changes in lunar radio temperature on the 0.86 cm wavelength during an eclipse and it is formed by a substance which resembles dry sand. Radio emission on a 0.86 cm wavelength is not significantly absorbed in the upper layer and it emanates primarily from the underlying layer, consisting of a pumice-type material. The thermal conductivity of this material, according to the author's calculations, is 16 times greater than for the upper layer ($\gamma \approx 250$). Since, during lunation, the temperature of the underlying layer is not constant, as during an eclipse, the variable part of radio emission during the lunar cycle gives information concerning the absorption of this layer. The author indicates, however, that this two-layer model is not in agreement with lunation measurements on longer wavelengths ($\lambda \approx 3.2$ cm), since the presence of a surface layer must lead, in his opinion, to effective temperature amplitudes which are larger than those observed[1]. In order to eliminate the existing controversy a conclusion is made concerning the three-layer structure of the lunar surface. Here it is assumed that the second layer has a thickness which is equivalent to the penetration depth of a 1 cm wave. The third layer has a higher thermal conductivity than the second layer, and may be formed by materials which are analogous to terrestrial rocks. The cited considerations, although physically correct, are quantitatively open to criticism, since on one hand they are based on old values of density and dielectric constant (taking $\rho = 2$, $\epsilon = 5$), and on the other hand ρ and k are considered to be independent. In addition, the observation of the integral emission during an eclipse leads to the smoothing of the radio temperature drop. This was not taken into account by the author. In view of this, Gibson's model is insufficiently substantiated, /620
although one might expect a certain decrease of density of matter closer to the surface (see also References 9, 32).

Thus, the variable thermal condition controlled by the sun enabled the establishment of layer properties down to the depth $l_{\text{э}} = 2\lambda l_T \cong 150$ cm through measurement of the amplitude of the variable part of radio emission. Deeper probing with longer wavelengths does not give reliable numbers for the variable component and therefore cannot give information concerning these layers.

At the same time it is found that, due to the presence of thermal flux from the interior of the moon, there exists a considerable temperature gradient into the interior. This gradient was established by the authors of this review in Reference 63. This offers the possibility of studying the layer parameters from the nature of temperature distribution

[1] In reality the presence of a thermally nonconductive layer leads to a decrease of the amplitude of oscillations; see Section 3, formula (20).

into the interior, which is measured by the determination of the dependence of the constant radio emission component on wavelength (see Section 3).

As a result of this precise method for radio temperature measurements it was possible to detect and to measure the temperature gradient into the interior of the moon to 20 m in depth. The gradient was found to be practically constant along its whole length, which indicates homogeneity of the layer to 15-20 m in depth.

It is apparent that the conducted analysis established only the principal character of the layer - its approximate uniformity, but it could not and cannot answer the question of the physical parameters of the layer and the microstructure of its substance (dust, solid, etc.). These answers are given by analysis of the most absolute values of radio temperatures and of other data, treated below.

6. Thermal Properties of the Lunar Crust

In 1930 Pettit and Nicholson (Ref. 5) on the basis of experimental data which they obtained during the lunar eclipse in 1927, indicated that the sharp temperature drop of the lunar surface during the time of passage of the penumbra is caused by low thermal conductivity of the lunar surface material. While analyzing the results of this eclipse Epstein (Ref. 64) came to the conclusion that the parameter γ for lunar matter is close to 120. Since this quantity is characteristic of porous terrestrial rocks of the pumice type, it follows that the lunar surface is covered with porous material. However, Epstein's calculations were erroneous. Rigorous calculations, as shown by Wesselink (Ref. 1), Jaeger and Harper (Ref. 59), whose works were treated in Section 2, leads to a significantly larger value of parameter γ for the lunar surface, which, according to their calculations, is equal to 1000. Assuming that for the substance on the lunar surface $\rho = 2$ g/cm^2 and $c = 0.2$, they found that the value $\gamma = 1000$ corresponds to the thermal conductivity coefficient $k = 2.5 \cdot 10^{-6}$ cal/cm·sec·deg. The investigations of Smoluchowskiy (Ref. 65) show that such low values of thermal conductivity are possessed by fine dust in vacuum.

Jaeger (Ref. 2) attempted to determine the parameter γ from calculated curves of temperature variation in the course of the whole lunar cycle by comparing it with the measured surface temperature during the lunar midnight ($T_H = 120^\circ K \pm 15^\circ$) from the measurements of Pettit and Nicholson. However, an inaccurate knowledge of T_H enabled them to establish only that this temperature corresponds to the value of γ which lies within $200 \leq \gamma \leq 1000$ limits.

In Reference 82 Fremlin gives the dependence of the thermal conductivity coefficient for lunar craters as a function of the depth as $k\ (y) = 7 \cdot 10^{-7} \sqrt{y}$. For the surface of the crater the value of k is taken to be that at 1 cm depth, i.e., $k_{surf} = 7 \cdot 10^{-7}$ cal/cm.sec.deg. However, as Jaeger has indicated, this value is unreasonably low and contradicts the results of Pettit (Ref. 58) as well as the recently completed work of Saari and Shorthil (Ref. 83), where the results of measurements on the individual lunar craters during an eclipse in the infrared wavelength region are presented. /621

A more accurate value of night temperature was determined quite recently by Sinton (Ref. 66) as $T_H = 122 \pm 3^oK$. According to Reference 66 this temperature corresponds to the value $\gamma = 430$. Jaeger (Ref. 2) indicated that the accurate knowledge of radio temperature changes in the course of a lunar cycle may be utilized for determination of the parameter γ.

In Reference 3 comparions of the electrical characteristics of the lunar surface (obtained from the analysis of data on lunar radio emission) with electrical characteristics of terrestrial rocks established that the density of the upper crust of the moon is of the order of 0.5 g/cm^3. On the basis of the obtained magnitude of density and the value $\gamma = 1000$ generally accepted at the time, the value of the thermal conductivity coefficient was evaluated as $k = 10^{-5}$. This is one order of magnitude smaller than that obtained in References 1 and 2 which corresponds more to porous pumice-like material than to dust in vacuum.

Attempts to determine the thermal properties of the lunar surface from radio emission data were undertaken by A. Ye. Salomonovich (Ref. 9). He conducted comparisons of the experimental phase change of lunar radio temperature on different wavelengths with the theoretical temperature phase change, obtained on the basis of corrected calculations (Ref. 2) for higher temperatures of a sunlit point. However, due to the low accuracy of absolute values of radio temperature the experimental data satisfied, as in Jaeger's work, the value of parameter γ lying within the following limits $300 \leq \gamma \leq 1000$.

With the development of a precision measurement method for lunar radio emissions (Ref. 24) the possibility was opened for a sufficiently accurate determination of the thermal properties of the lunar surface. This was performed in Reference 67 by the authors of this review. For this purpose the previously mentioned special calculations of thermal conditions were conducted (Ref. 4). These calculations were performed for a homogeneous structure and temperature, independent of the thermal properties of the lunar crust.

Figure 5 represents the relationships obtained in Reference 4 for the temperature of a sunlit point T_m, constant component $T_0(0)$, the first harmonic T_1 and night temperature T_H as a function of parameter γ for the center of the lunar disk.

In Reference 67 thermal parameters of lunar matter are determined by the use of the indicated calculations and the results of the precision measurements of lunar radio temperature.

With the significant increase in the accuracy of absolute radio measurements the values of the constant component of the mean effective temperature over the lunar disk have been reliably established on different wavelengths. Neglecting the weak wavelength dependence, resulting from the presence of the thermal flux from the interior of the moon, the value for the mean effective temperature along the disk measured on a 3.2 cm wave is $\overline{T}_{eo} = 211 \pm 2^{o}K$[1]. Using the relationship $\beta_o(\epsilon)$ (see Figure 8) and the result which showed that the constant component of the true surface temperature is $229^oK \leq T_0(0) \leq 236^oK$ according to Figure 5 this corresponds to $250 \leq \gamma \leq 450$. /622

Another value of γ was obtained in Reference 67 from the ratio T_0/T_1. The theoretical dependence of T_0/T_1 on γ is represented in Figure 17. Determination of the T_0/T_1 ratio does not require the knowledge of emissivity and stems from the relative measurements of the intensity of lunar radio emission in a broad wavelength interval. It is the limit of the ratio of the constant radio emission component to the amplitude of the variable component at $\lambda \to 0$. According to Reference 3,

$$\frac{T_0(0)}{T_1(0)} = 1.5 \pm 0.1.$$

1 This value is a mean of two precision measurements given in Table 2.

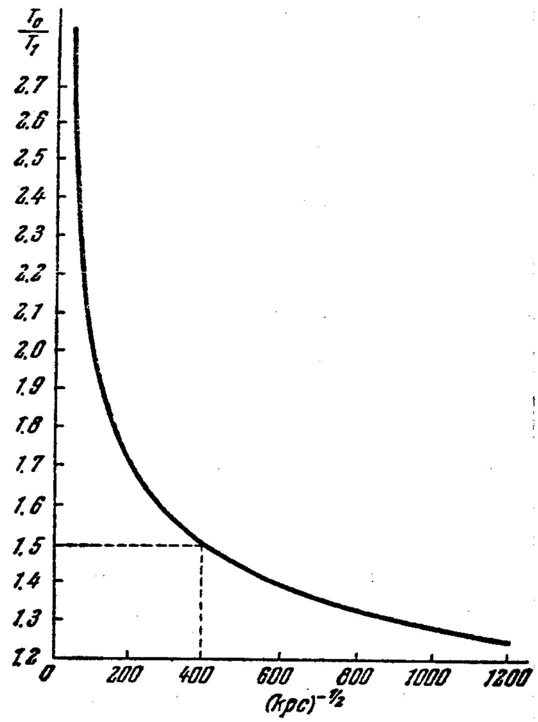

Figure 17. The ratio of constant component of temperature to the first harmonic of surface temperature in the center of the lunar disk as a function of parameter $\gamma = (k\rho c)^{-1/2}$

the indicated value of the ratio $T_0(0)/T_1(0)$ corresponds to the value of parameter $270 \le \gamma \le 550$ (from Figure 17). Finally, the quantity γ was determined in Reference 67 from temperature measurements on infrared waves during the lunar midnight. The comparison of the recently obtained value of night temperature by Sinton, $T_H = 122 \pm 3^{\circ}K$ (Ref. 67) with the curve $T_H(\gamma)$ in Figure 5 gives $350 \le \gamma \le 430$. Thus, one relative or two absolute completely independent measurements of the different characteristics of the thermal process lead to practically the same interval of values of γ. From here it is possible to argue with a great degree of reliability that the most probable value for γ with an accuracy not less than $\pm$ 20 percent is $\gamma = 350$.

With the density of rock $\rho = 0.5$ g/cm^3 and $c = 0.2$ we obtain for the thermal conductivity coefficient a value $k = (1 \pm 0.5) \times 10^{-4}$ cal/cm·sec·deg. The obtained quantity k is almost 50 times larger than the value which was determined in References 1, 2, and corresponds most

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probably to a porous pumice-like substance for the upper crust of the moon, and not to dust. Using the obtained values of the thermal conductivity coefficient we shall evaluate the depth of penetration of the thermal wave

$$l_\tau = \sqrt{\frac{k\tau}{\varrho c\pi}} \approx 25 \text{ см.} \tag{35}$$

It is of interest to note the discrepancy of the values of γ, determined from the temperature change curve during an eclipse ($\gamma \approx 1000$) (Refs. 1, 2) and during lunation ($\gamma = 350 - 400$) (Refs. 66, 67), falling outside the limits of possible measurement errors.

Considering the established approximate homogeneity of properties of the surface layer into the depth, the indicated discrepancy cannot be explained by the presence of a two-layer dust structure. It is possible that is associated with the properties of matter in the upper crust of /623 the moon as a function of temperature or with gradual decrease of density near the surface. It is necessary to note that the attempt to account for the temperature dependence of properties was undertaken in Reference 84. Assuming that k and c linearly change with temperature and comparing the constant temperature component on the surface from the results of Pettit and Nicholson (Ref. 5) and Piddington and Minnett (Ref. 7) the author evaluates parameter γ as $\approx 200 - 300$.

Since the consideration in Reference 84 is limited only to the constant component and the approximate relationship of k and c to the temperature, for further improvement of the values of γ and k it is necessary to rigorously solve the problem of thermal conditions, taking accurately into account k and c as a function of temperature.

7. Density and Dielectric Constant of Rocks in the Lunar Crust

Despite the fact that investigations of radio emission have been in progress for two decades, only recently were methods proposed for measuring or determining the density and dielectric constant of the lunar crust. In foreign literature, to the present time, the density and dielectric constant of lunar rocks, in analogy to the density and dielectric constant of terrestrial rocks (Refs. 15, 33, 60, 62, 66) are taken as $\varrho = 2$ and $\epsilon \approx 4$-5.

It is extremely important to note that in the works of foreign authors, treating a sharply discontinuous two layer model, the density is assumed to be the same even for layers with sharply different magnitudes of thermal conductivity (Refs. 15, 62). In reality, as it known from the theory of thermal conductivity, the magnitude of the latter for depends on the degree of its porosity P, which is in turn equal to the ratio of the volume of vacant space to the volume of filled space. The magnitude of porosity determines the mean density of substance ρ or its bulk mass, and it is equal to

$$P = 1 - \frac{\varrho}{\varrho_0},$$

where ρ_o is the density of substance in the nonporous state. Thus, thermal conductivity of any material is represented by the functions k (P) and k (ρ). This situation attracted the attention of one of the authors of this review and in Reference 68 it was proposed to use the relationship k (ρ) for the determination of the lunar matter density from the measured value of thermal parameter γ.

This method is based on the following reasoning. For any rock or combination of rocks, including the rocks which form the upper crust of the moon, the quantity $\gamma = (k\rho c)^{-1/2}$ must be a single valued function of density ρ, since thermal conductivity is a function of ρ, and c (specific heat) is independent of density. As a result one obtains

$$\gamma(\varrho) = (k(\varrho)\varrho c)^{-\frac{1}{2}}.$$

As quantity γ for the moon is known directly from measurements, then if function k (ρ) is known for lunar matter in a vacuum it would not be difficult to find density ρ. It is possible that a different structure such as hard foam or loose grains, functions k (ρ) will be different and will depend also on pore sizes or grain sizes. Thus, generally speaking, it is necessary to differentiate function k_1 (ρ) and function k_2 (ρ) for foamy and loose structures respectively.

The problem of determining density is consequently reduced to the determination of function k (ρ) for lunar matter. In connection with this it was indicated in the cited work that as lunar matter consists of ordinary silicate minerals, just as terrestrial rocks, function k (ρ) must be the same for the substance of lunar surface as for terrestrial rocks. In this connection it was shown from the available literature data on thermal conductivity of silicate materials in air that for foamy as well as for loose materials thermal conductivity in the $0.4 \leq \rho \leq 1.5$ density interval is described by the expression /624

$$k(\varrho) = \alpha\varrho = 0.6 \cdot 10^{-3}\varrho,$$

which is a universal function for the silicate group. At density $\rho > 1.5$ the quantity k may also be approximated by a straight line but with greater

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slope. From the obtained relationship from thermal conductivity in air, conclusions are also drawn concerning the thermal conductivity in a vacuum. It is considered that the straight line relationship of thermal conductivity as a function of ρ is preserved, and that only the proportionality constant α is changed. The magnitude of α_{vac} is determined from the isolated data which exists in the literature on thermal conductivity of silicate materials in a vacuum. It is found that for greater than 30 percent porosity, foam type materials decrease on the average by a factor of three and

$$k_1 = 2 \cdot 10^{-4} \rho, \qquad 0.2 \leq \rho < 1.5.$$

For loose materials a decrease of thermal conductivity as compared with its value in air reaches 10-20 times and is dependent on the particle size. For extremely small grain size we obtain

$$k_2 = 5 \cdot 10^{-5} \rho, \qquad 0.2 \leq \rho < 1.5.$$

These expressions were found for terrestrial rocks and are assumed to hold also for lunar rocks. Substituting functions k_1 and k_2 into the expression for γ and considering the found value of $\gamma = 350$, we obtain for the density of foam structure

$$\rho_1 = \frac{160}{\gamma} = (0.4 \pm 0.1)\,g/cm^3 \qquad (36)$$

For the density of loose structure we obtain

$$\rho_2 = \frac{320}{\gamma} = (0.9 \pm 0.2)\,g/cm^3 \qquad (37)$$

There are several methods proposed for the determination of a dielectric constant. Some of these methods were used for making measurements. It is shown in Reference 3 that a knowledge of the dielectric constant of lunar matter is important for the determination of its structure as well as the state of its surface. In reality the dielectric constant of any specimen of matter in the case of radio waves, depends on its porosity P or density ρ just as thermal conductivity does. The same substance with a different degree of porosity will have different dielectric constants. The greater the porosity the smaller the dielectric constant for a given sample. Ultimately with a very small amount of substance in the volume it will naturally approach unity: the dielectric constant of a vacuum. Thus, $\varepsilon = \varepsilon\,(P\varepsilon_0)$, where ε_0 is the dielectric constant of the nonporous specimen. Generally, one uses the following formula

$$\varepsilon = \varepsilon_0 \left(1 - \frac{3P}{\frac{2\varepsilon_0+1}{\varepsilon_0-1} - P}\right). \tag{38}$$

This formula is sufficiently well known both theoretically and experimentally and it enables determination of porosity with a knowledge of ϵ_0 and measurement of ϵ. Knowledge of ϱ_0 enables determination of the density of the rock ϱ. It is found that on superhigh frequencies ϵ_0 for all silicate rocks is practically identical (Ref. 69). Therefore, for the determination of ϱ it is necessary to know only the values of ϵ and ϱ_0. Thus we can see a complete analogy to the measurement of ϱ from quantity γ. /625

In order to determine a more precise relationship of ϵ as a function of ϱ NIRFI conducted many measurements of dielectric constants of different dry terrestrial rocks, for which the following empirical relationship was found (Ref. 69)

$$\sqrt{\varepsilon} - 1 = c\varrho, \tag{39}$$

where coefficient c ≈ 0.5 cm^3/g. This formula gives results which are close to theoretical; however, it is preferred since it was obtained for terrestrial rocks whose composition is probably close to lunar rocks.

How can we measure the dielectric constant of lunar rocks? In order to answer this question it is apparently necessary to analyze how the dielectric constant effects phenomena which are observed by means of radio telescopes. There appear to be many possibilities and methods. The first of the proposed and realized methods lies in the comparision of the measured radio temperature with the true temperature of the observed section of the lunar surface. It can be seen from formula (14) that by measuring the constant component of radio temperature in the center of the disk

$$T_{e0} = (1 - R_{\perp})\, T_0(0)$$

and knowing the constant component of true temperature $T_0(0)$, it is possible to fine the emissivity, $1 = R_{\perp}$ and ϵ from Fresnel's formula, if the surface of the moon is considered to be smooth for given wavelengths.

Apparently, the same may be done with a variable component, using the artificial moon method. In this case it is necessary to utilize the constant component for integral emission, equal to (see note on page 19)

$$\overline{T}_{e0} = (1 - R_{\perp})\alpha \cdot 0.964\, T_0(0),$$

where $(1 - R_{\perp})\alpha$ is the mean spherical emissivity and $0.964 \cdot T_0(0) = \overline{T}_0$ -- the mean constant component over the lunar disk. From the precision measurements on $\alpha = 3.2$ cm $\overline{T}_{e0} = 211 \pm 2^{\circ}$ K was obtained. The magnitude of T_0 is known from infrared measurements and heat calculations, while $\overline{T}_0 = 0.964\, T_0(0) = 218^{\circ}$ K. In Reference 12 of the authors it was found that the mean spherical emissivity is equal to

$$(1 - R_{\perp})\alpha = 0.96.$$

From this, using the computer calculations for α we obtain

$$R_{\perp} \approx 2\%,$$

from which the dielectric constant is

$$\varepsilon \approx 1.5.$$

Another method, used in References 20, 22, consists of direct measurements of radio brightness distribution over the lunar disk, i.e., functions of emissivity $1-R(r\epsilon)$. The nature of this function is completely determined by quantity ϵ. This method has advantages over the first method because measurements are relative; however, it requires the use of highly directional antennas. The results of measurement of the distribution of the constant component of radio brightness show that the observed change of the emissivity curve corresponds to the quantity ϵ, included within the following limits /626

$$1 \leqslant \varepsilon \leqslant 2.$$

The third method was proposed in Reference 70 and is based on the measurement of the degree of polarization of radiation from any section of the lunar surface. In actuality if the temperature of a section is equal to T_0, then for vertically and horizontally polarized radiation its radio brightness will be respectively as follows

$$T_{ev} = T_0(1 - R_v) \text{ and } T_{eh} = T_0(1 - R_h).$$

The degree of polarization, expressed to the measured quantities T_{ev} and and T_{eh}, will be equal to

$$\frac{T_{eh}-T_{ev}}{T_{eh}+T_{ev}} \approx \frac{R_v-R_h}{2}.$$

For smooth surfaces, R_v and R_h are known and their difference depends on ϵ, which enables its determination. It is possible to use also the relationship between T_{eh} and T_{ev}. The polarization measurements are also relative; however, they require the use of sufficiently high directionality. It is not difficult to see that for the observed small values of ϵ the greatest polarization will take place near the edges of the lunar disk, where the angle of incidence r to the surface will be close to the Bruster angle, equal to approximately 30-45°. This corresponds to the removal of the platform from the edge of the disk by approximately 4-5 angular minutes. This quantity determines the width of the required directivity diagram of the antenna.

The polarization method for determination of ϵ was used by N. S. Soboleva (Ref. 71). Observations were conducted on a 3.2 cm wave on the large Pulkovo radio telescope, having a knife-edge type directivity diagram. This gave the mean polarization value in the band which intersects the lunar disk along the vertical. As a result of the processing of measurement data the dielectric constant was found to be equal to

$$\varepsilon \approx 1.65 \pm 0.05.$$

The fourth method of measuring ϵ was proposed in Reference 72. This method is based on the determination of the radio emission phase lag from sections of the lunar disk located on different longitudes along the equator of the moon in comparison with the heating phase of the corresponding sections of the circle.

From all of the obtained values of ϵ, equal on the average to 1.5, and from formulae (38) and (39) it follows that the mean density of the lunar surface rocks in the layer whose thickness is not less than the penetration depth of a 3 cm wave, i.e., about 1.5 m, is equal to

$$\varrho \approx 0.5 \text{ g/cm}^3.$$

By comparison of the obtained values of ϱ with independently determined values from thermal measurements (from the magnitude of γ) we see that the values coincide and support the foamy-state concept. It shall be proven experimentally that approximately the same density of material prevails at a depth of 20 m. This again indicates that the substance is not pulverized and is not a deep layer of fine shifting dust, as was proposed in Gold's hypothesis (Ref. 55).

8. The Nature of the Substance in the Lunar Crust /627

For study of the properties of the lunar upper crust in the optical wavelength region one conducts a comparison of certain characteristics of the lunar surface (lightness, color, scattering coefficient, polarizability) with the corresponding characteristics of the terrestrial volcanic rocks. In this area extensive experimental material has been accumulated, and conclusions have been made regarding the possible composition and structure of the lunar surface (Ref. 73). However, optical methods of comparison give information only regarding the thin surface layer, whose properties may differ significantly from the properties of deeper layers. In addition, these methods are not adequate for determining the nature of the substance. It is well known that a number of similar rocks which are found in nature possess different coloration and reflectivity (black or white pumice, different quartzes having most diversified coloration, etc.), which frequently depend on a negligible amount of impurity. Such characteristics as light scattering and polarization during reflection are even less helpful for the determination of the chemical nature of substances, since such characteristics depend primarily not on the composition, but on the surface geometry, the nature of roughness and the degree of upheaval. With the development of radio astronomy a new possibility was offered for the investigation of the nature of the lunar upper crust by comparison of the electrical properties of the lunar surface (ϵ and $\tan \Delta$) with the electrical properties of rocks and minerals.

Investigations of lunar radio emission have shown that its surface is a good dielectric ($\tan \Delta \ll 1$), for which, in the broad wavelength interval (from 0.4 to 3.2 cm) $\tan \Delta$ is practically independent of the wavelength (Ref. 3). Recently this was verified down to $\lambda = 0.13$ cm (see Table 2). Analogous properties are possessed by alumosilicate base dielectrics.

The attempts to compare terrestrial rocks with materials on the lunar crust according to the magnitude of dielectric permeability and electrical conductivity (or $\tan \Delta$) was made by a group of authors (Refs. 62, 74), but without the consideration of the dependence of ϵ and $\tan \Delta$ on the density of material, and therefore similar comparison is possible if one uses such characteristics which are independent of density. In Reference 3 it is shown that the specific tangent of the dielectric angle is such a characteristic, and is equal to the ratio $\tan \Delta/\rho$. This quantity is invariant with respect to density ρ and depends principally on the chemical composition of the material. In Reference 3, a relationship was obtained from expression (34), which connects electrical and thermal parameters of the lunar surface material: $\frac{\sqrt{\epsilon}\tan \Delta}{\rho} = 88 \cdot 10^{-6}\ c\gamma$.

Taking $c = 0.2$, $\epsilon = 1.5 \pm 0.3$ and $\gamma = 350 \pm 75$ (Ref. 67) we obtain the following value for the lunar surface material: $\tan \Delta/\varrho = (0.5 \pm 0.3)\cdot$

$\cdot 10^{-3}$. The measurement of quantity $\tan \Delta'/\varrho'$ for terrestrial rocks enables the determination of the group of rocks which have a like value for this invariable quantity and probably correspond to rocks which form the lunar upper crust.

There are relatively few works which are dedicated to the study of the electrical parameters of terrestrial rocks. In Reference 74 for the interpretation of radar characteristics of lunar reflections, measurements of dielectric and magnetic permeability and dielectric losses were conducted for a large number of terrestrial rocks, stony meteorites and tektites. The authors of Reference 74 also investigated the effect of the degree of subdivision of material on the magnitude of dielectric permeability. However, dielectric characteristics of the terrestrial rocks were measured only on audio frequencies, and therefore it is not possible to use the data of these authors for comparison with lunar material characteristics, which were measured on superhigh frequencies. The same work gives the results of measurements of ϵ and $\tan \Delta$ in the 420-1800 mc range for two specimens of stony meteorites of the chondrite type. /628

Detailed measurements of electrical characteristics of tektites on the 60 cm wave were conducted in Reference 75 where 15 specimens of tektites, found in different areas of the earth, were studied. Of these, 5 were australites, 3 indochenites, 1 moldavite, 4 philippinites, and 1 was silica glass from the Libyan desert. The results of these measurements are given in Table 3. The dielectric permeability, determined for the naturally dense state (ϱ_0 for all measured specimens lies within $2.4 \leq \varrho_0 \leq 2.5$ limits) of all specimens changes very insignificantly ($6.0 \leq \epsilon_0 \leq 7.4$) and dielectric losses are very small and vary within insignificant limits ($0.43\cdot 10^{-3} \leq \tan \Delta \leq 3.4\cdot 10^{-3}$). From the results of Reference 75 we calculated the dielectric permeability for the porous state ($\varrho \approx 0.5$ g/cm^{-3}) and the specific tangent of the dielectric loss angle by the use of the Odelevskiy-Levin formula. The results of these calculations are also given in Table 3.

Measurements were made of a large number of rocks having diversified chemical composition (from acid to basic) on different wavelengths at NIRFI (Ref. 69). Specimens were measured on 0.8, 3.2 and 10 cm waves in the natural as well as in a crushed state. This enabled determination of the dependence of dielectric permeability and tangent of the dielectric angle on the wavelength and on the density ϱ. They were preliminarily dried for 2 hours at 200-250° C to remove adsorbed moisture. As a result /629

Table 3. Dielectric Constant and Tangent of Dielectric Loss Angle of Tektites on 60 cm Wave

Name	Australites						Indochinites	
Mean content of SiO_2, %	70.0						73.3	
No.	17 A	17 B	17 C	17 D	17 E	17 F	18 A	18 B
	2.42	2.43	2.45	2.45	2.41	2.46	2.40	2.37
ϵ	6.53	6.41	6.65	6.39	6.58	7.2	6.29	6.85
$\epsilon_{0.5}$	1.73	1.73	1.75	1.73	1.74	1.80	1.73	1.80
$\tan \Delta$	$34 \cdot 10^{-3}$	$7.5 \cdot 10^{-3}$	$12.0 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$16.0 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$	$0.43 \cdot 10^{-3}$
$\tan\Delta/\varrho$	$14.05 \cdot 10^{-3}$	$3.9 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$6.64 \cdot 10^{-3}$	$3.17 \cdot 10^{-3}$	$1.96 \cdot 10^{-3}$	$0.18 \cdot 10^{-3}$

Name	Indochinites	Moldavites	Silica glass	Philippinites			
Mean content of SiO_2, %	73.3	78.0	97.6	71.64			
No.	18 C	19 A	20 A	21 A	21 B	21 C	21 D
	2.40	2.35	2.20	2.44	2.42	2.49	2.44
ϵ	6.00	6.09	4.16	6.09	7.41	6.76	7.11
$\epsilon_{0.5}$	1.70	1.72	1.53	1.72	1.84	1.75	1.81
$\tan \Delta$	$5.3 \cdot 10^{-3}$	$9.1 \cdot 10^{-3}$	$0.46 \cdot 10^{-3}$	$4.4 \cdot 10^{-3}$	$17 \cdot 10^{-3}$	$6.5 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$
$\tan \Delta/\varrho$	$2.21 \cdot 10^{-3}$	$3.87 \cdot 10^{-3}$	$0.21 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$	$7.02 \cdot 10^{-3}$	$2.61 \cdot 10^{-3}$	$2.75 \cdot 10^{-3}$

of this study it was found that for all rocks the magnitude of tan Δ remains approximately constant in the indicated wavelength region.

Measurements on samples with a different degree of crushing have established that the ratio tan Δ/ρ is independent of density with an accuracy of ±15 percent.

It was established that quantity /630

$$\frac{\sqrt{\varepsilon}-1}{\rho}$$

is also independent of the density and changes insignificantly for different rocks with an accuracy of ±5-7 percent. The results of measurements obtained in Reference 69 are given in Table 4. This table also gives the values of ϵ, calculated for density $\rho = 0.5$ by formula (39). The information which was obtained in References 69, 74 and 75 regarding the electrical characteristics of terrestrial rocks, meteorites and tektites enable a comparison according to Reference 3, and to establish the nature of those terrestrial substances, which have a similar value of tan Δ/ρ, with lunar surface material. These substances apparently correspond to the material which forms the lunar upper crust.

Figure 18 shows the values of tan Δ/ρ which were obtained in Reference 69 and also those which were determined from the data of References 74, 75 for different terrestrial rocks, meteorites and tektites as a function of the SiO_2 content, which characterizes the basicity of the material.[1]

The shaded area corresponds to the value of tan $\Delta/\rho = (0.5 \pm 0.3) \cdot 10^{-2}$ which was determined for the material on the lunar surface. This area includes terrestrial rocks of different basicity: acid (liparite, granite, ingimbride) neutral (syenite, diorite) and basic (iolite, gabbro). It is extremely interesting that almost all of the measured tektites (Ref. 75) have the same specific losses as the lunar surface material. In our opinion this favors the hypothesis regarding the lunar origin of tektites. /631

Such terrestrial rocks as basalt, dunite, volcanic ash and tuff as well as stony meteorites of the chondrite type have specific losses which are much greater than those for the lunar surface (tan $\Delta/\rho \approx (1.5\text{-}2) \cdot 10^{-2}$). Consequently these materials do not fall into the "lunar" region.

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[1]Since in References 74, 75, the chemical composition of the investigated specimens was not specified, and the experimental points were plotted, we used mean values of the SiO_2 content determined from the literature.

Table 4. Dielectric Constant and Specific Tangent of Dielectric Loss Angle of Terrestrial Rocks on 3.2 cm Wave

Name	Density range	% SiO_2	$\frac{\sqrt{\epsilon}-1}{\rho}$	$\frac{\tan\Delta}{\rho}$	ϵ (ρ= 0.5)
1. Quartz sand	1.24	98	0.4	0.001	1.44
2. Obsidian	1.18–2.26	74.9	0.57	0.011	1.65
3. Ingambride	0.9 –1.15	72.9	0.50	0.0066	1.56
4. Liparite	11.8 –2.35	72.7	0.47	0.0024	1.53
5. Granite	1.2 –2.48	71.2	0.46	0.004	1.51
6. White pumice	0.42–0.7	69.2	0.68	0.015	1.8
7. Black pumice	0.3 –0.7	68.54	0.64	0.01	1.74
8. Tuff 1	0.57–1.2	62.5	0.64	0.0126	1.74
9. Tuff 2	0.65–1.24	60.5	0.57	0.013	1.65
10. Tuff 3	0.9 –1.85	62.7	0.61	0.011	1.72
11. Trachytic lava	1.18–13	60.1	0.52	0.01	1.59
12. Volcanic ash 1	0.93	52.0	0.60	0.013	1.69
13. Volcanic ash 2	0.77	65.2	0.62	0.015	1.72
14. Volcanic ash 3	1.34	62.0	0.55	0.013	1.63
15. Volcanic ash 4	1.69	64.0	0.48	0.01	1.54
16. Volcanic ash 5	1.32	52.5	0.5	0.015	1.56
17. Volcanic ash 6	1.43	53.4	0.55	0.013	1.63
18. Volcanic ash 7	1.2	55.0	0.53	0.014	1.60
19. Volcanic ash 8	1.05	56	0.53	0.014	1.60
20. Quartz syenite	1.24–1.38	64	0.51	0.004	1.58
21. Syenite	1.25–2.5	56.9	0.51	0.007	1.58
22. Andesitic basalt	1.23–2.36	58.4	0.52	0.013	1.59
23. Diorite	1.2 –2.53	58.9	0.47	0.006	1.53
24. Gabbro 1	1.3 –1.5	54.4	0.50	0.003	1.56
25. Gabbro 2	1.26–1.36	48.2	0.53	0.003	1.60
26. Basalt 1	1.34–2.55	49.1	0.52	0.017	1.59
27. Basalt 2	1.3 –2.55	49.0	0.53	0.018	1.60
28. Ijolite	1.3 –1.54	42.8	0.53	0.005	1.60
29. Dunite	1.26–2.56	40.5	0.52	0.02	1.59
30. Dolerite	1.26–1.42	48.0	0.54	0.023	1.61

Recalculation to density 0.5 g/cm³ was done by the formula $\frac{\sqrt{\epsilon}-1}{\rho} = \propto$

This means that even if these substances enter into the composition of the lunar surface, their quantities are such that they do not determine the dielectric properties of the surface of the moon. Figure 18 very convincingly shows the characteristic mineralogical and chemical composition of lunar matter. It is most probable that it consists of 60-65 percent quartz, 15-20 percent aluminum oxide and the remaining 20 percent is comprised of potassium, sodium, calcium, iron and magnesium oxides. However, as we have seen, rocks or mixtures of minerals which form the substance of the lunar upper crust must be in an extremely porous state, and in this respect they do not resemble the ordinary dense terrestrial rocks.

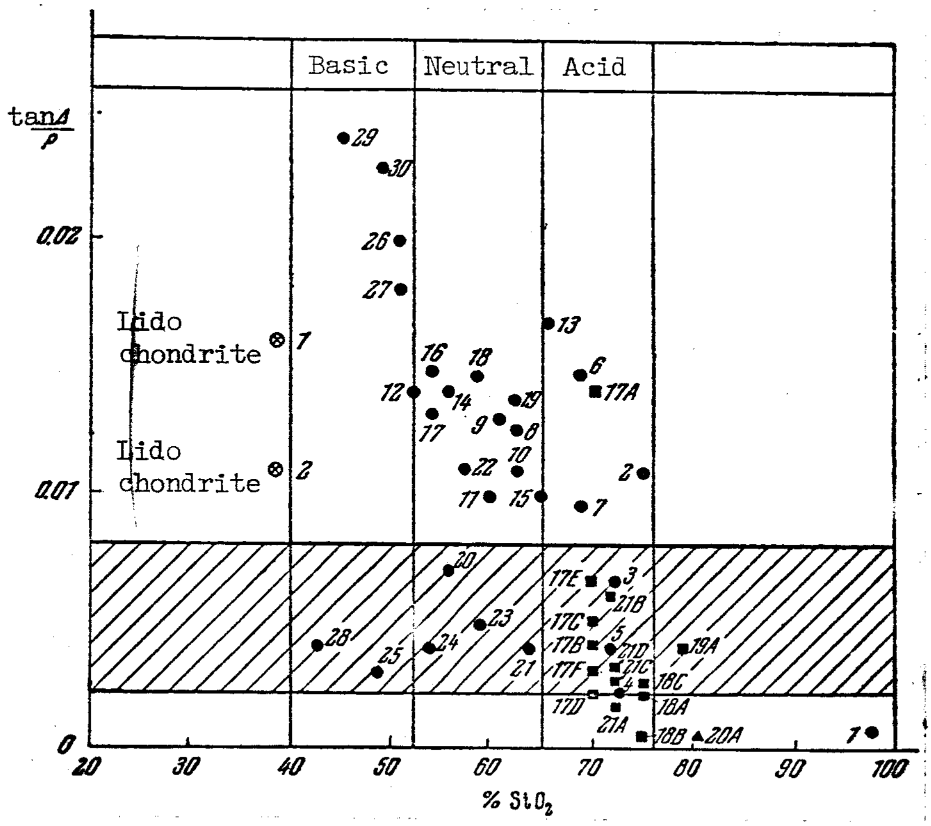

Figure 18. The ratio $\tan \Delta/\rho$ as a function of the percent content of SiO_2 for different rocks, meteorites and tektites. Numbers correspond to the specimen number in Tables 3 or 4.

There are many other finer differences which are determined optically. All this forces one to find a new name for the material of the lunar upper crust which is now frequently proposed in literature. In our investigations it is now named lunite.

It is necessary to note that the cited magnitudes of specific losses are mean values for the whole lunar surface and therefore they indicate only the mean mineralogical and chemical composition. In connection with this it is possible that different sections of the lunar surface may consist of different rocks.

There are hypotheses according to which the lunar seas are formed by basic basaltic rocks and the continents by acid rocks of the granite type. If this is so, then radio emission studies would easily show the difference in rocks which comprise the lunar seas and continents.

At present there are no special measurements made to verify this. However, the measurements of the intensity distribution of radio emission along the lunar disk conducted in Reference 20 on the 0.8 cm wave indicate most probably the absence of insignificant effects resulting from the difference of lunar rocks. Recently, special measurements were made of radio emissions from the lunar seas and continents on the 0.4 and 0.8 cm waves (Ref. 76) with the use of a high resolution radio telescope. The result is that the section located in the region of a lunar sea had an effective temperature which is several degrees greater than the section located in the continent region. The obtained difference may testify in favor of some difference in the thermal properties of seas and continents. However, the measurements of the phase shift of radio emission for different equatorial regions on the 0.4 cm waves (Ref. 29) did not show any significant differences in the amplitude of the oscillation phase.

The incomplete data presently available only allows the conclusion that the thermal properties and chemical composition of the whole lunar surface are predominantly uniform.

9. Thermal Radiation from the Lunar Interior, and the Thermal State of the Lunar Interior. /632

It was shown in Section 3 that the constant component of lunar radio emission is determined by the layer temperature at the depth of $l_э$ of penetration of an electromagnetic wave. In Section 5 it was established that for lunar rocks, just as for terrestrial rocks, the law of linear increase of $l_э$ with the increase of the wavelength λ is valid (formula 34). In connection with this the possibility is offered to determine changes of temperature in the interior of the moon.

It can be seen from Table 2 that by now there is a sufficiently large amount of published data on lunar temperature on different wavelengths, from millimeter to meter waves, characterizing the temperature values at different depths beneath the surface of the moon.

However, attempts to determine from these data the expected systematic increase of temperature with an increase of wavelength, undertaken by Messger (Ref. 46) and Mayer (see Ref. 77), were fruitless. It is apparent from Table 2 that the scattering of values of the constant lunar temperature component, given by different authors (with the exception of data obtained by the "artificial moon" method), reaches ±40-50° K and with such information it is not possible to determine a systematic increase of temperature.

In an attempt to find and measure the temperature gradient in the lunar interior, Baldwin (Ref. 15) undertook special measurements of the lunar radio emission on the 160 cm wave. The method of measurement was based on the comparison of lunar radio emission with cosmic radio emission which it screens. In actuality a small difference was measured between the effective temperature of the moon and the background screened by it. As a result of this, measurement errors of small differences associated with the inaccuracy of calibration and knowledge of the antenna parameters effect the results insignificantly. However, for determination of the radio temperature of the moon it was necessary to know the radio temperature of the screen background. The author believes that the magnitude of the background was known with much better accuracy than ±10 percent, as is now believed. Consequently, the 168 cm wave gives for the mean radio temperature over the lunar disk a value of $\bar{T}_L$ with an uncertainty of ±3 percent. The measured quantity $\bar{T}_L = 233 \pm 8^\circ$ K. To characterize the accuracy of the measurements themselves it should be noted that the indicated quantity is obtained from two measurements, which give the minimum temperature in a series of eight measurements. The scattering of lunar temperature in the whole series reached 100° K.

Baldwin did not have an accurate value of radio temperature on the shorter wavelength, and therefore for further calculations he was forced to use the theoretical value of constant component of the mean temperature on the surface $T_0 = 222^\circ$ K (Ref. 2). This author believes that the increase of temperature on the 168 cm wave does not exceed 25° and he explains this as the result of thermal flux from the lunar interior. Assuming a homogeneous model for the structure of the lunar crust down to the penetration depth of a 168 cm wave (about 60 meters) he found the values for the thermal flux density, $q_s \leq 0.25 \cdot 10^{-6}$ cal/cm·sec, which coincides with the theoretical evaluation (Refs. 78-80). Setting aside the question of the accuracy of these measurements, which is apparently claimed to be much too high, we first note that the quantity of the increase of temperature itself (25°) is not much larger than the underestimated error claimed by the author (8°). This makes evaluation of the thermal flux unreliable. Secondly, it is hardly valid to consider a 60 m layer to be homogeneous in density. Naturally, lower layers may be denser. This will lead to the penetration depth of the 168 cm electromagnetic waves being in reality smaller and the evaluation of thermal flux with this in mind will change it in the direction of much larger values.

As a result of the development of methods which insure the high accuracy of measurements of radio emission flux it became possible to investigate and solve the problem of determining the thermal flux from the lunar interior. /633

In Reference 16 evaluations were made of the thermal flux on the basis of precision measurements of lunar radio emissions in the centimeter range of wavelengths. However the small wavelength interval, and consequently the small temperature increase, as compared with the experimental errors, gave only an evaluation of the upper boundary of the thermal flux density as $q_s \leq 4 \cdot 10^{-6}$ cal/cm^{2}sec.

The question on thermal flux was treated in Reference 63 by the authors of this review, where analyses are given for the results of precision measurements of lunar radio emission on the 0.4, 1.6, 3.2, 9.6, 32.3, 35 and 50 cm waves made in 1961-1962 (Refs. 24, 30, 35, 36, 38, 40, 50, 52, 53) and given in Table 2. Figure 19 shows the relationship which was obtained as a result of the indicated measurements for the constant component of radio temperature as a function of the wavelength. The above-mentioned work (Ref. 63) stresses the possibility of errors in measurements due to the effects of the ionosphere, cosmic radio emission background, blocking by the moon and the disk and other factors which become more and more significant with the increase of wavelength.

If one doubts that the observed effect was caused by an increase of lunar radio temperature then one must admit the existence of a significant cosmic radio emission background, the difference of which in the directions at the disk and at the moon for large galactic latitudes must reach 25-30° on the 35-50 cm wave. This explanation, not supported by the direct measurement of the background, would require basic reconsideration of the theory of the origin of cosmic radio emissions and would possibly touch upon the basic concepts regarding the properties of the cosmic medium.

A question arises as to whether the observed increase of radio temperature results from the thermal flux from the lunar interior. Generally speaking it is possible to produce a number of other causes: reflection of solar radio emission by the moon, cosmic radio emission or emission from sources which exist on the earth, dependence of the lunar thermal properties on temperature (nonlinearity of the thermal

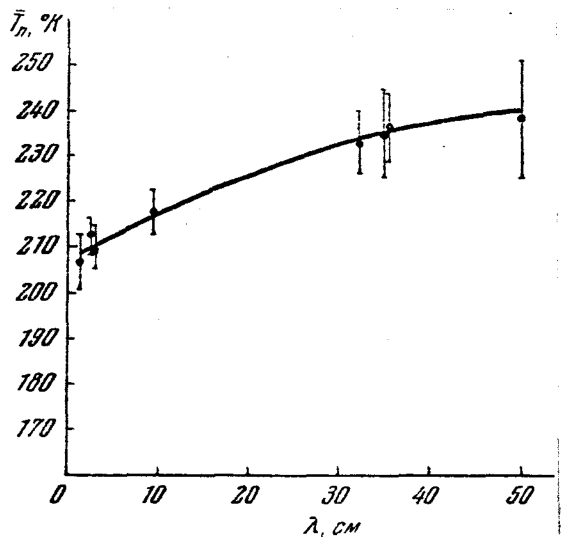

Figure 19. The mean effective temperature over the lunar disk as a function of wavelength. From the precision measurement data of lunar radio emission.

conductivity equations), and finally, increase of emissivity of the lunar surface with increase of wavelength. Calculations have shown that when the reflection coefficient R = 2 percent the increase of radio temperature due to reflection of solar radio emission would be equal to $\Delta T = 10^{-7} T_\bullet$, where $T_\bullet$ is the radio temperature of the sun for a given wavelength. From here it follows that even on the meter waves ($T_\bullet \approx 10^6$ °K) the increase of radio temperature will be negligible. Increase which is caused by the reflection of cosmic radio emission on $\lambda = 50$ cm is found to be of the order of $\Delta T \approx 0.05°$ K. The effect of emission of radio stations on the earth in the 10-50 cm range is also negligible. On the meter waves used by television, however, Shklovskiy has indicated /634
the radio brightness of the earth may be significant, and this in turn will "lighten" the moon analogously to lightening from solar radiation.

The nonlinearity of the thermal conductivity equations for lunar matter is principally based on the relationship of heat capacity to temperature. Here, the constant component of temperature due to solar heating will depend on the amplitude of temperature oscillations. Since the latter varies in depth, the constant component will depend on the depth and consequently on the wavelength. It is clear that this dependence will take place down to the depth not greater than (3-4) $l_T \approx 100$ cm.

The constant component will be invariable for greater depths. Thus, the whole change of the constant component may be observed only in the wavelength interval from the millimeter waves up to the 3-4 cm waves. However, the principal increase of radio temperature is observed on waves greater than 3 cm. The nonlinearity of the medium may change only the initial course of the curve for the radio temperature as a function of the wavelength.

The assumption regarding the increase of the black body conditions with the increase of wavelength also cannot be ascribed within the framework of known concepts. In view of coarseness one would expect improvement of the reflecting properties of the moon with longer wavelengths, which would cause the decrease of the effective temperature with the increase of wavelength.

Thus, the only possible explanation for the observed effect would be the existence of thermal flux from the interior of the moon. The almost linear increase of the lunar radio temperature with an increase of wavelength from $\lambda = 0.4$ cm to $\lambda = 35$ cm, as shown in Figure 19, indicates approximately constant thermal conductivity from the very surface to the penetration depth of the 35 cm wave. This in turn means that according to the established relationship between thermal conductivity and the density of substance (Section 7), the density of substance in the whole layer is approximately constant and equal to the above-determined density of the surface layer. Consequently, for the whole layer where a 35 cm wave penetrates, the relationship (34) is valid

$$l_э = 2\lambda l_т, \qquad 0.1\ см \leqslant \lambda \leqslant 35\ см.$$

According to this the penetration depth of a 35 cm wave is $l_э = 20$ m.

Some deviation of the value of lunar radio temperature for $\lambda = 50$ cm from the value which would correspond to a linear increase may indicate the increase of the density of the lunar substance at a depth of 20 m. From Figure 19 the slope of the curve is equal on the average to $(T_{\lambda 2} - T_{\lambda 1})/$ $/(\lambda_2 - \lambda_1) = 0.8$ deg/cm. From formula (28) at $l_T = 25$ cm the temperature gradient in a 20 m layer is equal to

$$\text{grad}\ T(y) = 1.6\ \text{deg/m}$$

From formula (29), taking $\gamma = 350$, we find that the density of thermal flux from the lunar interior is equal to

$$q_s = 1.3 \cdot 10^{-6}\ \text{cal/cm}^2\text{sec}$$

The total thermal flux from the lunar interior will be equal to

$$Q = 1.6 \cdot 10^{19} \text{ cal/year}$$

The obtained value of the thermal flux density for the moon is practically equal to the thermal flux density of the interior of the earth (see note in correction at the end of this article). The theoretical evaluation of the possible thermal flux from the moon was made by McDonald (Ref. 80), Levin (Ref. 79) and Jaeger (Ref. 78), assuming chondrite composition of lunar rock leads to significantly smaller magnitudes $q_s = (0.2\text{-}0.3) \cdot 10^{-6}$ cal/cm^{2}sec. The values of flux density which we ob- /635 tain are 4-5 times greater than the theoretical evaluation. From the determined total lunar thermal flux it follows that for a gram of lunar matter the following number of calories of radiogenic heat are liberated per year

$$q_v = 2.2 \cdot 10^{-7} \text{ cal/g year}$$

From the latest data, radioactive elements contained in stony meteorites generate, according to different literature sources, from $0.4 \cdot 10^{-7}$ to $1 \cdot 10^{-7}$ cal/g·year. For the earth the volume density of the generated radiogenic heat is only equal to

$$q_v = 0.35 \cdot 10^{-7} \text{ cal/g year}$$

Such a low value is associated with the large quantity of iron inside the earth, in which the content of radioactive elements is one order of magnitude smaller than in stony meteorites. The values of q_s and q_v will de decrease by a factor of 2 if one takes $\gamma = 700$, or close to that value which follows from the infrared measurements during a lunar eclipse.

The obtained high value of radiogenic heat contradicts the hypothesis on formation of the moon from meteor chondrite-type substances and will require basic reconsideration of the concepts of the thermal history of the moon which were based on the previously indicated low values of the content of radioactive elements in the lunar matter.

In Reference 63 the following conclusions are made:

1. High temperature gradient in surface layer at least 20 m in thickness results from low thermal conductivity of the substance in this layer. In view of the uniform layer the magnitude of thermal conductivity in it is everywhere approximately the same and is equal to the

previously found 1 m thick layer. Thus, one of the new conclusions is the high porosity of substance even at depths of several tens of meters. It is apparent that this substance cannot be dust. Low density and low thermal conductivity may be preserved at these depths if the substance is sufficiently strong and not subjected to compression from the over layers.

2. In the case of the moon the thermal conductivity of its upper rock beds is determined by the degree of their porosity or density. At a given depth the rocks will have the characteristic density of a nonporous state and the same thermal conductivity as they have on the earth. Consequently, the thermal conductivity of deep-lying rocks must increase 40-60 times as compared with thermal conductivity in the considered upper layer. The temperature gradient at these depths, as can be easily calculated, will equal the temperature gradient on the earth, i.e., 1/30 of a degree per meter of depth. This will apparently take place at a depth of several hundred meters.

3. For the evaluation of the probable temperature in the lunar interior it is necessary to know the distribution of radioactive elements in the interior. The minimum estimate of temperature will be obtained if all of the elements are concentrated in the surface layer. Let us assume that it consists of granite: the most radioactive rock, 1 gram of which liberates $7 \cdot 10^{-6}$ cal/year. It is not difficult to find that the 20 km layer of granite will insure the experimentally-found value of thermal flux. Apparently, as in the earth, the upper radioactive layer consists of granite, lying on a basalt base. If one assumes, as for the earth, an equivalent layer of about 60 km and also that at a depth of 60 km the thermal flux falls to 0, then it is not difficult to find that at this depth the temperature must be $1/2 \cdot 1/30 \cdot 6 \cdot 10^4 \approx 1000^\circ$ K. The temperature will apparently not change at deeper levels. The more uniform the distribution, the higher will be the temperature of the deep interior. /636

Conclusion

10. Future Problems in Lunar Investigation by Radio Emission

We shall note only those problems which must be attacked directly after the previously solved problems and which exist within the circle of the discussed questions. These include first of all, the problems of a finer and more detailed investigation of the physical and structural parameters (density, thermal conductivity) of the layer with depth. This problem requires theoretical investigations of the lunar radio emission in the case of a nonhomogeneous upper layer. The difficulty of this problem lies in the fact that all heat equations and integrals for radio emission may be solved numerically only by a computer. The result of calculations must contain spectra of the principal characteristics of lunar radio emissions which are obtained in the experiment: amplitude of intensity oscillations, phase lag and others.

Along with the problem of considering any possible inhomogeneity effect of the surface layer on the nature of radio emission, the problem arises of accounting for the temperature dependence of the thermal and electrical properties of the moon. In the temperature interval which takes place on the moon, heat capacity, for example, may change by a factor of a few units, and the change of the dielectric loss angle is also very sensitive. All this may significantly change the nature of the spectral characteristics of radio emission as compared with the spectrum for a homogeneous model during temperature independence of these properties. In reality the results presented previously are only the first and possibly rough approximations.

To find the indicated properties of the upper layer (some inhomogeneity of density, temperature dependence of thermal and electrical properties), further measurement of radio emission will be required, almost in a continuous wavelength range from infrared to decimeter wavelengths. In addition, it is also necessary to determine precisely the constant component. Specifically, the work must be conducted on the determination of layer properties which lie below the depth where temperature fluctuations are significant (depth greater than $4\ l_T \sim 100$ cm).

The properties of this layer may be investigated due to the discovery of thermal flux from the interior of the moon. Here, the main difficulty is experimental. It is necessary to conduct accurate measurements of lunar radio emission up to the 1.5-2 m waves, which will possibly enable penetration down to a depth of 100-140 m and to find the nature of changes of thermal conductivity and density in this layer. Accurate measurements in this range are in this range are extremely difficult and require first of all accurate absolute measurements of cosmic background of radio emission.

The problem of construction of the model of the upper layer of the moon, which would incorporate all radio emission data, will require laboratory investigations of the thermal conductivity and dielectric loss angle of rocks in a broad wavelength interval. Here a large problem appears, which is still not solved by heat physics, concerning the determination of the dependence of thermal conductivity of rocks (or silicate materials) in a vacuum, on porosity, pore or grain size, and on temperature.

There are still not enough data on the electrical conductivity of terrestrial rocks in the superhigh frequency range, particularly at low temperatures. The invariance of $\tan \Delta/\varepsilon$ has not been verified for densities larger than 1.5-2 $g{\cdot}cm^{-3}$. /637

However, in reality all the indicated problems may be solved only for the whole lunar hemisphere, thus giving a mean characteristic which in a number of cases may differ from the characteristics of individual parts of the lunar surface. In connection with this appears the problem of investigating the degree of inhomogeneity of the lunar crust properties and individual formations. This is possible only with the use of large radio telescopes. In particular, it is possible to solve the problem of determining the electrical properties (angle of dielectric losses) of matter for the lunar seas and continents, which will enable the establishment of their nature or at least will determine whether they are made of the same or of different material. This can finally solve the dispute between different hypotheses on the nature of the seas and continents.

The small amount of available data on lunar investigations by means of high resolution radio telescopes (down to 2-3 minutes) thus far indicates uniformity of properties of the lunar crust over the whole lunar disk. It will hardly be possible to greatly advance the investigation of small details by radio emission, since the satisfactory resolution may be presently obtained only for waves which are shorter than 1 cm, and which cannot penetrate any deeper than 0.5 m. Thus, individual details of the lunar relief may be probed from the earth only from the surface down to this depth and no further. The thought should be abandoned of probing individual sections of the moon to the depth of tens of meters. The technical difficulties of investigation of individual characteristics of the lunar relief by means of radio emission are extremely great.

An important area of investigation of physical conditions on various details of the lunar surface (volcanos, craters, etc.) may be the measurement of lunar submillimeter infrared radiation. However, investigations of lunar relief details and their physical characteristics will probably pass into the hands of astronauts, who we believe will shortly step on the lunar surface.

A Remark Added During Correction

The question arises regarding the interpretation of the undoubtedly existing thermal flux. We believe that in principle there may be only two possible explanations: either this flux is of solar origin or, as in the case of the earth, it results from the decay of radioactive elements (mainly uranium, potassium-40 and thorium), contained in all rocks. The first explanation requires extremely far-fetched assumptions regarding the penetration of at least 10^{-3} component of solar radiation to a depth of tens of meters. However, in the case of a decimeter wave one would observe a significant phase shift of radio emission, which thus far has not been found. Only one noncontradictory explanation remains: that the thermal flux stems from the interior and, as in the case of the earth, has radiogenic origin.

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